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13. ABSTRACT *(Maximum 200 words)*

In order to develop a mechanically simple and robust actuator for active flow separation control on axial compressor blades, three different types of acoustic transducers were tested in a wind tunnel. Flow separation on a cylinder in cross flow was used. The first transducer had an internally mounted acoustic speaker blowing through a slot. It could control flow separation only for low Reynolds number laminar flows. A flush mounted high-frequency circular piezo-electric transducer was tried next. It was marginally effective only around the laminar-turbulent transition regime. Since it could not focus the perturbations over a small area, the "Acoustosurf" was developed next. It consisted of an array of flush mounted narrow strip shaped acoustic transducers capable of detecting surface pressure fluctuations prior to separation. When the appropriate strips were excited at the predominant fluctuation frequency, separation was delayed for transitional and tripped flows. It is believed that the Acoustosurf produces a synergistic interaction between roughness, surface compliance and acoustic radiation to redirect the kinetic energy of the flow by exploiting flow instabilities. Negligible power is therefore needed to operate the Acoustosurf. This has attracted the attention of several aircraft manufacturers.

14. SUBJECT TERMS Unsteady Flow Separation Control, Acoustic Active Surfaces

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I. INTRODUCTION

The principal motivation for this project was to develop a mechanically simple method of controlling flow separation on axial compressor blades. It was clear that some form of active control would be needed. However, traditional forms of active separation control, such as moving flaps or blowing/suction were eliminated. It was believed that a radically new approach was needed since an extension of existing methods would not achieve the desired objectives. Acoustic transducers were chosen primarily because of their mechanical simplicity.

During the first year of this project, ideas were borrowed from published literature (e.g. Ahuja and Burrin, 1984; Hsiao et al., 1990). This led to the evaluation of a traditional speaker mounted under the surface of the test model (a 152-mm diameter circular cylinder in cross flow). The speaker communicated with the surface through a slot. This arrangement was found capable of controlling flow separation, as evidenced from a measurement of time averaged surface pressures. However, it was believed that the interaction with the separating boundary layer was primarily mechanical, resulting from the periodic blowing and suction through the slot. Since then, hot-film measurements have confirmed that blowing and suction velocities have to be comparable to the freestream velocities for effective control. Therefore, the speaker needs a significant amount of vibrational displacement for this method to work, since in principle it is identical to boundary layer blowing and suction. This implies that large-displacement low-frequency actuators will be needed. The mechanical complexity and relatively large size of such an actuator therefore makes it impractical for compressor blades. Finally, the primary interaction mechanism for this type of actuator is not acoustic radiation. It was therefore not known whether pure acoustic radiation emanating from the surface could control flow separation effectively.

In order to study the effect of pure acoustic radiation in the absence of blowing, suction or other mechanical perturbation, a new transducer was needed. Subsequent efforts therefore focused on this area. The principal results from this work have been reported in three papers (Sinha and Pal, 1993a,b, and 1994) which are included in the appendix. **The details of the wind tunnel testing apparatus and procedures are described in these papers**. Additional details can be obtained from the M.S. Thesis of Dipankar Pal (Pal, 1993). This work has also resulted in an invention, the "Acoustosurf" (see section on commercial applications). Therefore, the publication of the results in archival journals will only be attempted after patent applications have been filed. The following section outlines the significant results from this work.

II. EFFECT OF DIFFERENT ACTUATOR DESIGNS ON FLOW SEPARATION CONTROL

Following the experiments with the acoustic speaker driven exciter (Figure 1a.), a circular piezo-electric transducer, mounted flush with the surface of the test cylinder (Figure 1b.) was investigated. The main reason for this choice was that the power needed to control separation increased with flow Reynolds number. However, the design of the speaker prevented additional power to be put into the flow. At low frequencies (i.e. less than 1-kHz), which corresponded to the optimum frequencies for control at low-speed laminar flow Reynolds numbers, the speaker was found to interact with the flow by periodic blowing and suction through the slot. The

blowing and suction velocities at the mouth of the slot had to be comparable to the freestream velocity for adequate control. At larger velocities the blowing and suction component reduces and a larger fraction of the total energy is transferred to acoustic radiation. The energy content in the acoustic radiation is however too low to affect the flow. This is especially true in terms of the disturbances introduced due to the presence of the slot. Hence it was realized that the transducer design would have to be modified to minimize such disturbances. This led to the development of the flush-mounted piezo-electric transducer.

The piezo-electric transflexural element used in this transducer is used in a variety of beepers and buzzers. This transducer was incapable of generating a perceptible sound pressure level at frequencies below 2 kHz. With the test cylinder in cross flow in the wind-tunnel, a slight increase in the mean surface pressures resulted when the piezo-electric actuator was turned on. The previous speaker driven transducer had reduced the mean pressures. Hence, the drag on the cylinder increased. Maximum changes in mean surface pressures were observed when:

i) the transducer was centered around the mean unexcited separation point;

ii) the boundary layer was in the laminar-turbulent transition regime (i.e., Reynolds number based on cylinder diameter was around 1.5×10^5);

iii) and the excitation frequencies were in the 5-7kHz range.

Figure 2. shows a typical distribution of gains in time-averaged pressures on the top surface of the cylinder caused by excitation under optimal conditions. The pressure gain is defined as the increase in mean static pressure at a point obtained by simply turning on the acoustic exciter with the tunnel running at a constant speed. The optimum location and excitation frequency were determined through a search procedure. Compared to the speaker-slot excitation, the changes in pressures were extremely low, and the optimum frequencies were about an order of magnitude higher for similar flow Reynolds numbers. Figure 3. shows the corresponding spectra of velocity and surface pressure fluctuations. Both are generally reduced as a result of excitation, except for increases in pressure at the excitation frequency and its harmonics.

The circular piezo-electric transducer introduced negligible velocities at the wall (about three orders of magnitude lower than the freestream velocity, as measured with a laser-Doppler vibrometer or LDV). However, unlike the speaker-slot exciter, it did not perturb the flow in a localized quasi-two-dimensional fashion. The oscillation modes were in fact quite complex at the frequencies used, as predicted by theory (Warren, 1993), and confirmed by laser-Doppler vibrometer (LDV) measurements.

A third transducer was therefore designed which had a narrow strip-like shape, but did not introduce any mechanical unsteadiness (i.e. significant wall velocities). An array of such strips (also referred to as an "Acoustic Active Surface") was used (Figure 1c.). The reason for using an array, instead of a single strip, was to build in the capability of applying the acoustic excitation at the most effective spatial location for controlling unsteady separation. The design of this transducer posed some challenges, since the effective frequencies tend to increase with lower characteristic dimensions, such as the width of the strips. The constructional details, and

actuation mechanisms (i.e. Piezo-electric, electromagnetic etc.) of this transducer, are not being disclosed at present due to proprietary reasons.

Each strip in the above mentioned transducer could not only generate sound, but could also be used as a sensor for measuring surface pressure fluctuations. The transducer array was (nominally) flush mounted on one side of the test cylinder, with the strips aligned with the axis of the cylinder. Figure 4. shows the typical frequency responses of the strips. The pressure fluctuations sensed by the strips were monitored. The pressure spectrum from a transducer strip positioned just upstream of the mean separation point showed a peak, as indicated in Figure 5. The frequency corresponding to this peak (e.g. 2.25 kHz in Figure 5) was the most effective frequency to perturb the flow. The mean surface pressures on the surface of the cylinder changed significantly when a pair of strips at the optimum angular location were excited in-phase at 2.25 kHz (Figure 6.). The angular location at which the time-averaged velocities reduced, and velocity fluctuations increased, can be assumed to be the mean separation point. This point is seen to move downstream with acoustic excitation (Figure 7) thus providing a direct measure of separation control. Plate-1 shows a smoke flow visualization of the flow before and after exciting the surface confirming the velocity and pressure measurements. The improved pressure recovery as a result of this control reduced the form drag by about 12% and generated mean lift.

Since the acoustic active surface could not produce any measurable flow changes at flow Reynolds numbers below 1.4×10^5, it was perceived to be a transition promoter. In order to see the difference between acoustic excitation and other forms of transition promotion, the flow was tripped with a sandpaper strip. This caused the separation point to move downstream. The flow was then excited in this condition at a point close to the new separation point. This however did not produce any detectable changes. The point of excitation was subsequently moved back to where it was for the untripped situation. This increased the pressures in the wake as seen in Figure 8. The increased pressures in the wake region reduced the form-drag by about 20% and enhanced the generation of mean lift. Smoke visualization of the tripped flow (Plate-2) indicates that the separation point does indeed move slightly further downstream upon excitation. Also the degree of unsteadiness decreased upon excitation as observed visually from the smoke streaks. This can be seen clearly in the video recording of the flow visualization. The flow visualization observations and video also show that activation and de-activation of the surface act like a switch. The movement of the separation point is almost instantaneous.

III. AN INSIGHT INTO THE POSSIBLE INTERACTION MECHANISMS

The velocities of the surface of the strip-shaped transducers were once again found to be two orders of magnitude smaller than the freestream values. Initially it was thought that the transduder interacts with the flow only through acoustic radiation (Sinha and Pal, 1994) since changing the mechanical compliance of the surface did not affect the results as long as the change was not too great. Several surfaces were subsequently fabricated and tested. The design of the transducer was also changed to change the surface compliance and roughness. As long as some residual roughness remained (the height of the roughness elements were about 0.05 mm) the boundary layer was affected even with the surface unexcited. This effect also remained after the surface was "frozen up" to remove all compliance. This effect is seen for example in the unexcited pressure distribution in Figure 7 and can therefore be believed to be caused solely due

to roughness. Upon excitation, the amplitudes of the surface vibration were smaller (about 0.001 mm) than the roughness. Thus the way the surface interacts with the flow is through acoustic radiation in conjunction with some compliance and roughness. This transducer seems to be able to produce a synergistic combination of these effects (e.g. Gad-el-Hak, 1994).

At present it is believed that perturbation from the active surface significantly modifies the process of non-linear amplification of disturbances in the boundary layer during the transition process. This effect was confirmed by hot-film measurements in the wake. Excitation at 2.25 kHz is seen to significantly reduce velocity fluctuations centered around 25 Hz (Figure 9). The 25-Hz frequency corresponds to the vortex shedding frequency. Thus, "high-frequency" acoustic radiation emanating from a "line source" on the surface of the cylinder could control a "low-frequency" vortex shedding phenomenon. Additionally, time-averaged pressures and velocities could be changed by a strictly periodic (i.e., zero mean) excitation. Therefore, higher order non-linear effects, such as acoustic streaming, also occur.

The power consumed by the acoustic active surface was extremely small (in the order of micro-Watts). The power saved by drag reduction in the experiments was around 5-Watts. Hence an enormous amplification (about a million times) is seen. A minimum sound pressure level of 70 dB at the surface of the transducer was needed before any change was observed. However, increasing the sound pressure level did not improve the performance. It is believed that the surface cannot produce measurable changes unless the disturbances introduced can rise above those naturally present in the flow. Low amplitude (linear) acoustic excitation does not introduce a significant amount of energy into the flow; it merely modifies the way the energy is distributed between the mean and fluctuating components of velocity and pressure. A small perturbation such as this must therefore be introduced only at certain critical points for it to effectively control a higher energy boundary layer.

The wavelength of sound at 2.25 kHz is about an order of magnitude larger than the thickness of the pre-separated boundary layer, or the post-separated shear layer. Therefore, acoustic excitation at this frequency can be expected to excite the potential flow outside the boundary layer as well. The wavelength however did not correspond to any acoustic resonant frequencies in the wind tunnel or the lest section.

The present wind tunnel used for this study was unable to produce velocities larger than about 15 m/s in the test section. The cylinder used was the largest possible so as not to cause excessive blockage. Hence the flow Reynolds numbers could not be raised any higher than about 160,000. An experiment was carried out with a 30-cm chord NACA-0012 airfoil. The active surface was mounted between 5 and 25 percent of the chord from the leading edge on the suction side. Exciting the strips of the active surface did not produce any measurable change in the stalled and unstalled flows over this airfoil. The airfoil was operating at a chord based Reynolds number of about 300,000. Examination of the stall characteristics of the NACA 0012 showed that it was caused by laminar leading edge separation. Since the flow separated before transition it was not surprising that small-amplitude perturbations had no effect. The full significance of these results along with proposed additional results are outlined below.

IV. SUMMARY OF IMPORTANT RESULTS

Table 1 summarizes the results obtained from testing the three different acoustic transducers. The similarities and differences can be clearly seen.

Figure 10 provides a conceptual explanation of the mechanisms involved in controlling the flow with the acoustic active surface. The reasons for the need of a minimum flow Reynolds number, and a minimum sound pressure level are explained in terms of the receptivity of the flow to small disturbances. This also explains why a certain spatial location is the most effective point to excite the flow. Figure 10 shows this location to be the instability point.

The video of the flow visualization experiments is available with the PI.

V. DIRECTIONS FOR SUBSEQUENT PHASES OF WORK AND FUTURE RESEARCH

The efforts on this project to date have resulted in the successful development of the acoustic active surface and has demonstrated its capability for controlling unsteady flow separation on a cylinder. In this respect, the original objectives proposed have been reached, and the project is certainly on schedule. Several questions however remain unanswered, and additional studies are needed.

1. Additional measurements need to be made in various sections of the flow to determine changes in velocity profiles and wall shear stresses caused by acoustic excitation. At present some measurements are being made on zero pressure gradient boundary layers.

2. A rudimentary analysis will be attempted based on hydrodynamic stability theory. The main thrust of this effort will be to come up with a theoretical basis for the most effective excitation frequency. Although the effect of wall compliance and residual roughness have been discounted before, it seems a synergistic relationship between them and the acoustic field may hold the key to successful operation of the surface. It seems the surface does not work if the Reynolds number is lower than a critical value (about 100,000 for the cylinder). However upper limits of the Reynolds number need to be explored since most practical applications call for chord based Re values of several million. At present a second higher speed wind tunnel is being prepared for the higher Re tests.

3. At present, the signal from one of the strips was utilized to arrive at the most effective excitation frequency. However, this signal is not always very clean. Therefore, a method for filtering the noise needs to be developed. Hardware and software developed for active noise cancellation will be utilized for this purpose.

4. The best results reported thus far were based on exciting two adjacent transducer strips in phase. The effects of out-of-phase oscillations will be investigated. Additionally, an attempt will be made to close the sensor-actuator feedback loop.

5. The present results were based on flow separation over a cylinder. Experiments will be done

FEATURE	SPEAKER/SLOT EXCITER	CIRCULAR PIEZO EXCITER	STRIP ARRAY EXCITER
PERTURBATION CHARACERISTICS	ACOUSTIC RADIATION; BLOWING-SUCTION VELOCITIES COMPARABLE TO FREE STREAM. NOMINALLY 2-D PERTURBATION	PURE ACOUSTIC RADIATION; NEGLIGIBLE NORMAL VELOCITIES AT SURFACE. COMPLEX 3-D PERTURBATION	PURE ACOUSTIC RADIATION; NEGLIGIBLE NORMAL VELOCITIES AT SURFACE. NOMINALLY 2-D PERTURBATION
EFFECTIVE FREQUENCY RANGE FOR CONTROL	400 - 700 Hz	5 - 7 kHz	2.25 kHz
FLOW REYNOLDS NO. RANGES WHERE CONTROL IS POSSIBLE	FROM 6000 (LAMINAR) TO 1.5×10^5 (TRANSITION)	1.4×10^5 TO 1.6×10^5 (LAMINAR, TRANSITIONAL)	1.4×10^5 TO 1.6×10^5 (TRANSITIONAL AND TRIPPED)
POWER REQUIREMENTS	HIGHEST; CONTROL RANGE AND EFFECTIVENESS CAN BE EXTENDED BY INCREASING POWER INPUT	NEGLIGIBLE; MINIMUM SPL NEEDED (90 dB); INCREASING SPL DOES NOT HELP IN IMPROVING CONTROL	NEGLIGIBLE; MINIMUM SPL NEEDED (75 dB); INCREASING SPL DOES NOT HELP IN IMPROVING CONTROL
OPTIMUM EXCITATION LOCATION	UNEXCITED MEAN LAMINAR SEPARATION POINT	UNEXCITED MEAN LAMINAR SEPARATION POINT	UPSTREAM OF UNEXCITED MEAN LAMINAR SEPARATION POINT (EVEN FOR TRIPPED FLOW)
MEAN SURFACE PRESSURES	DECREASE AROUND POINT OF EXCITATION	INCREASE AROUND POINT OF EXCITATION	DECREASE AROUND POINT OF EXCITATION (UNTRIPPED); ALSO INCREASE IN WAKE (TRIPPED)
VELOCITY FLUCTUATIONS	INCREASE	DECREASE	DECREASE
FORM DRAG	REDUCES ??	INCREASES ??	DECREASES BY 10 TO 20%

Table 1. Summary of experimental results.

to see the effect of using the active surface to control separation over an NACA 0012 airfoil at high angles of attack.

Preliminary experiments on an NACA 0012 wing model did not indicate any effect due to surface excitation for chord based Re values up to 300,000. However, the separation characteristics of the NACA 0012 do not start showing high-Re characteristics till an Re value of about 600,000 is reached. The higher Re experiments are planned to be conducted in the wind tunnel mentioned above which is currently being modified for this purpose.

Additional tasks needed to be performed in order to determine the feasibility of using the surface on compressor blades include:

a) Investigating the effectiveness of the active surface on a test compressor blade.

b) Incorporating the active surface as a part of a disturbance amplification device to create a workable "high-stroke, broadband" actuator (identified as one of the priority areas in the Workshop on Inherent Non-Steadiness in Compressors and Turbines (WINCAT) at Purdue University, October 1993).

VI. POTENTIAL COMMERCIAL APPLICATIONS OF RESEARCH

This work has shown that it is possible to construct a mechanically simple acoustic actuator which can be used to control laminar-turbulent flow transition, and flow separation. At present, it is envisioned that the "acoustic active surface" can be applied to an existing aerodynamic surface, or preferably be incorporated as an integral part of the surface or structure. Since no mechanical moving parts, such as levers or flaps are involved, the structural integrity of the base component does not have to be compromised. A set of electrical connections is all that is needed to actuate the surface, and sense signals from it.

It therefore has the potential for meeting the original objectives of this project, namely controlling unsteady separation on axial compressor blades. In this application it can be used not only on the blades and guide vanes, but also on the inlet to the engine. The active surface can control inlet distortions and prevent the flow from separating on the compressor blades, thereby providing a means to mitigate rotating stall in military and civilian aircraft engines. Since very little external power is needed to drive the active surface, the size of the compressor, or the power of the engine should not pose any limitations. The power needed for control comes from the flow itself; the active surface merely redirects it. Furthermore, this form of "component level" active control can also be utilized to make the compressor physically smaller (e.g. by increasing the stage pressure ratios). This not only fits in with ongoing Air Force objectives such as IHPTET, but also provides another avenue for reducing the sizes and weights of commercial aircraft engines.

Another possible application of this surface is to delay the onset of separation leading to dynamic stall on helicopter rotor blades. Additionally, the surface can be used in a host of external and internal flow problems. These may include separation control and drag reduction for aircraft wings, and wing tips, drag reduction for trucks and other surface vehicles, and head loss

reduction in ducts.

At present, the possibility of applying for a patent is being considered while commercial interests are being gauged. The name "Acoustosurf" has been coined to designate the active surface. Therefore, the details of constructing this surface have not been divulged to date. Representatives from several aircraft companies have expressed an interest in the device. Representatives from three companies, (1) Cessna , (2) Beechcraft and (3) Learjet have visited the campus and were given a presentation of the capabilities of the device. While all acknowledged the possible use of this device in flow separation control on fixed and rotary wing aircraft, they declined from making definite commitments till the high-Re experiments showed promise. Recently, Dr. K. Saripalli, a representative from McDonnell Douglas Aircraft has expressed an interest in exploring the use of the "Acoustosurf" for controlling circulation over the tail boom of tail-rotorless helicopter (Saripalli, 1995). Bell Helicopters has also expressed an interest in the Acoustosurf if it can be shown to work under realistic Re and Ma conditions. The general response from companies has been that while the device holds promise further R&D efforts will be needed to turn this into a practical marketable product. The above mentioned companies were interested in the use of this surface for stall and separation control of aircraft. Inquiries have also been received from United Technologies Hamilton Standard for application of this surface to propellers.

An additional avenue is being explored by the P.I., Dr. Sinha; namely the use of the Acoustosurf in controlling mixing in combustors (Sinha and Pal, 1995). Although, the use of acoustic perturbations to control combustion is not new, the acoustic active surface may be able to exploit flow instabilities better than traditional low frequency woofers and piezo-electric transducers.

VII. PROJECT PERSONNEL/TRAINING OF GRADUATE STUDENTS

Two graduate students and four undergraduate seniors (Mr. Henry Lee Jones, Mr. Randel Harbur, Mr. J. Clark Love and Mr. Bradley Weston) have worked on this project. The type of work (e.g. constructing aerodynamic models, and using test instrumentation) has succeeded in stimulating Mr. Henry Lee Jones to get graduate degrees in Mechanical Engineering. Mr. Dipankar Pal, the graduate student who worked on this project since its inception, used this research as the basis of his M.S. Thesis. He is currently enrolled as a Ph.D. student at the University of Mississippi. He is continuing work in this area, and plans to use it towards his Ph.D. Dissertation. The second graduate student, Mr. Debjyoti Banerjee will be using results from this project for his M.S. Thesis.

Throughout this work expert advice was solicited from Dr. F. Douglas Shields (Research Professor of Physics and Astronomy and Project Co-Principal Investigator/Consultant); and from Dr. John Fox, (Professor Emeritus of Mechanical Engineering, and an expert on hydrodynamic stability).

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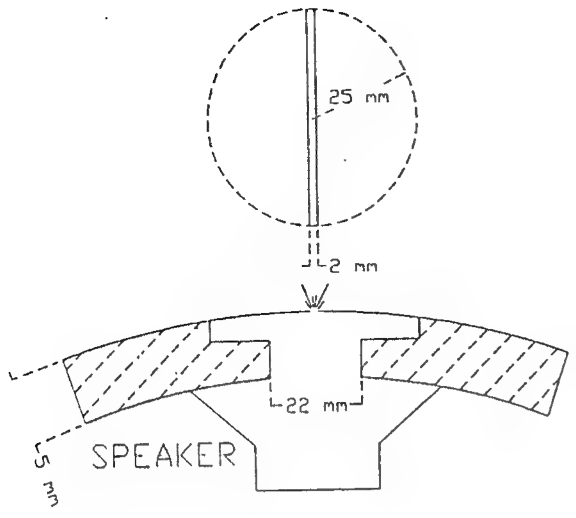


Figure 1 (a). Speaker-Slot Exciter

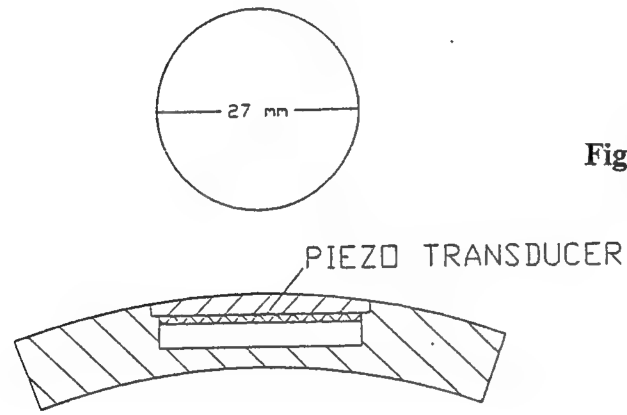


Figure 1 (b). Circular Piezo-Transducer

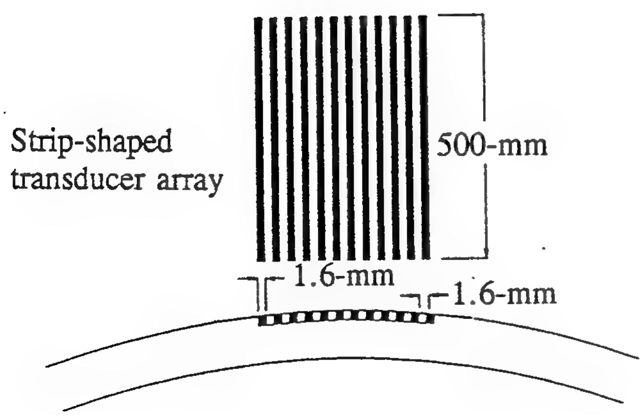


Figure 1 (c). Strip-Shaped Transducer

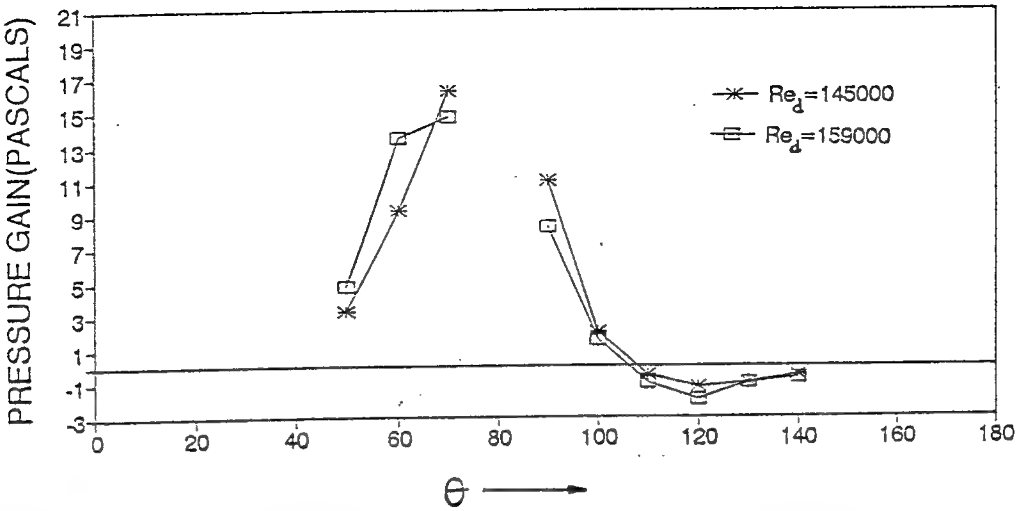


Figure 2. **Surface pressure gain at different angular locations under acoustic excitation. $f_a = 5.5$ kHz for $Re_d = 1.45 \times 10^5$, and $f_a = 7$ kHz for $Re_d = 1.59 \times 10^5$. Excitation at $\Theta = 80°$.**

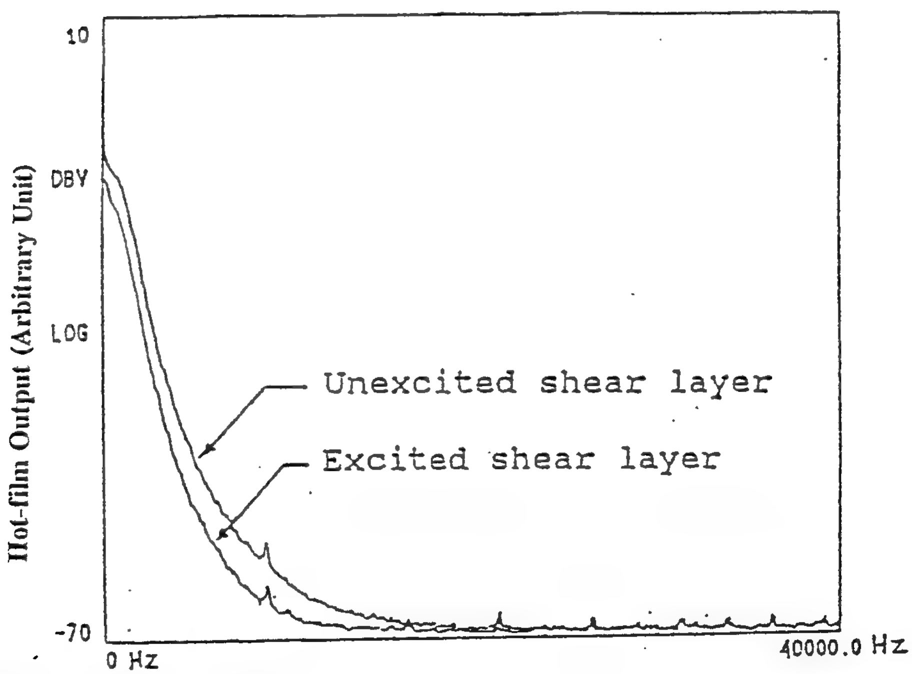


Figure 3a. **Time-averaged velocity spectra of unexcited and excited shear layers. $Re_d = 1.59 \times 10^5$, and $f_a = 7$ kHz.**

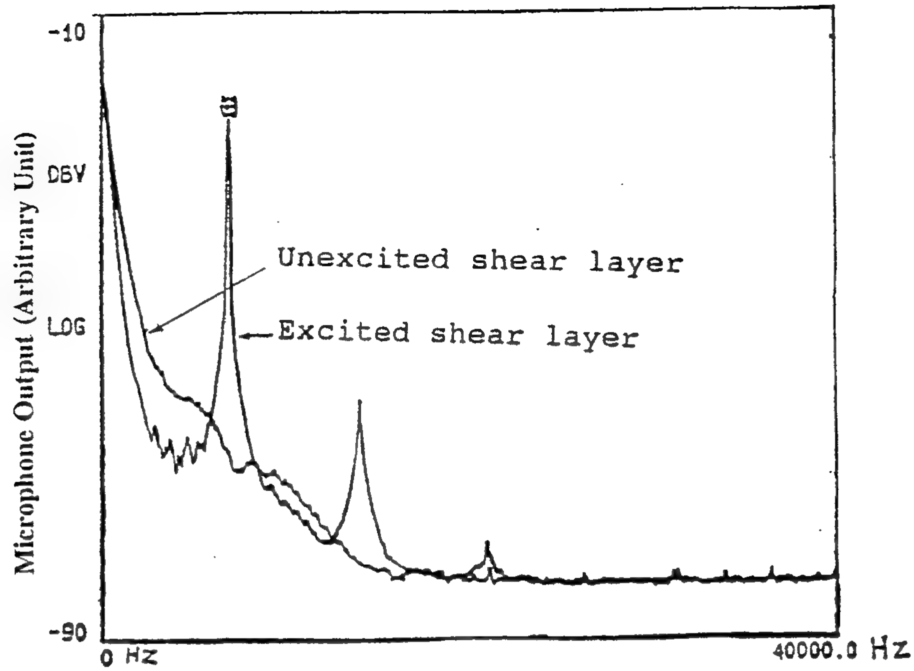


Figure 3b. Time-averaged pressure spectra of unexcited and excited shear layers. $Re_d = 1.59 \times 10^5$. Excitation at $\Theta = 80°$, and $f_a = 7$ kHz. Measurement location : $\Theta = 90°$.

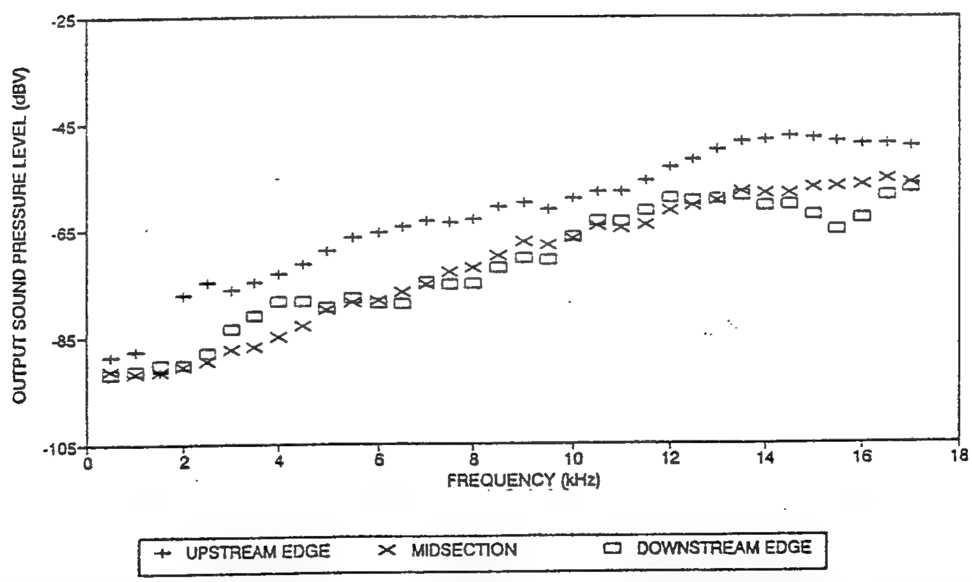


Figure 4. Acoustic frequency response of three different strip-shaped transducers (upstream edge, midsection and downstream edge) on the acoustically active surface.

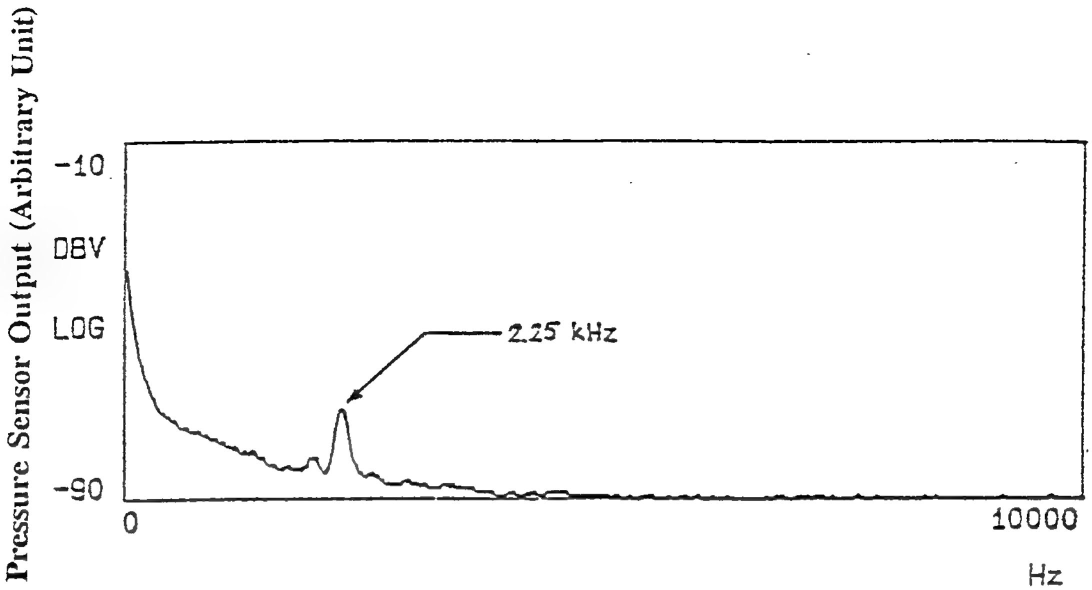


Figure 5. **Time-averaged surface pressure spectrum of pre-separation boundary layer in the absence of acoustic excitation.**
$Re_d = 1.5 \times 10^5$. Measurement location : $\Theta = 78°$.

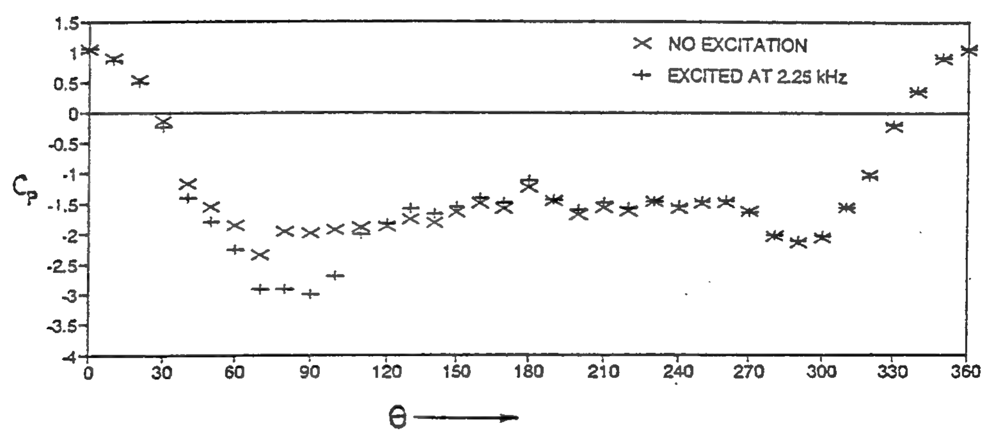


Figure 6. **Surface static pressure distribution (unexcited and excited flow states).** **$Re_d = 1.5 \times 10^5$. $f_a = 2.25$ kHz. Location of excitation : $\Theta = 72°$-$74°$ (multiple strip excitation).**

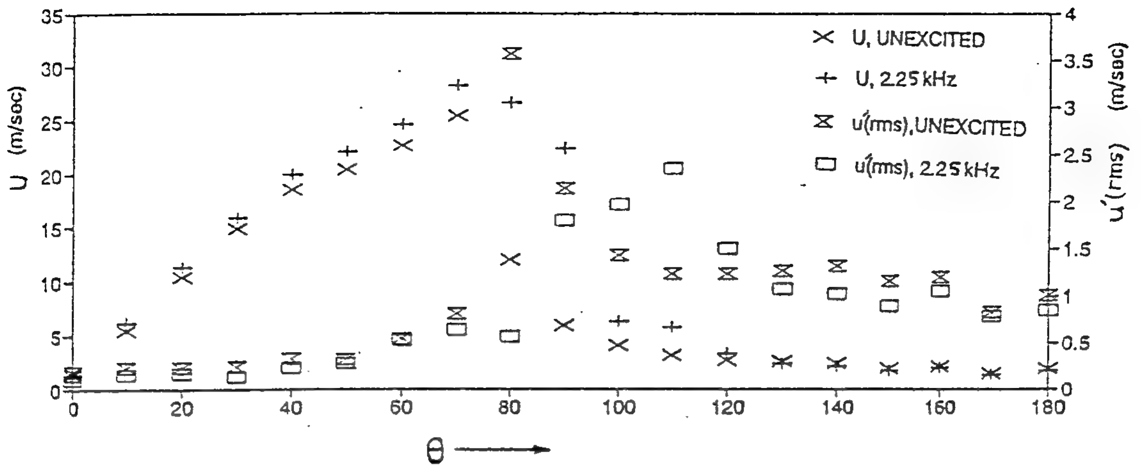


Figure 7. **Distribution of time-averaged mean and fluctuation velocities close to the cylinder surface. y = 1-mm for all measurement locations.**
$Re_d = 1.5 \times 10^5$. and $f_a = 2.25$ kHz.
Excitation location : $\theta = 72°$-$74°$ (multiple strip excitation).

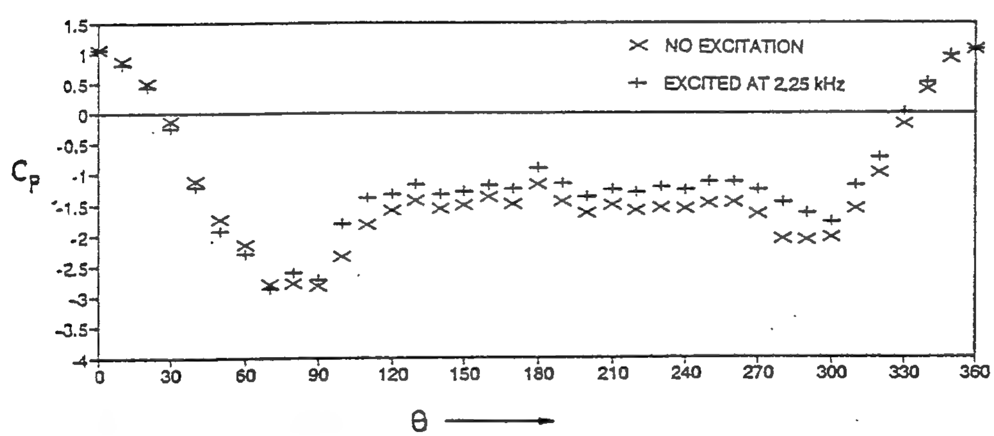


Figure 8. **Surface static pressure distribution (unexcited and excited flow states).**
$Re_d = 1.5 \times 10^5$. $f_a = 2.25$ kHz.
Artificial flow tripping at $\theta = 35°$.
Location of excitation : $\theta = 72°$-$74°$ (multiple strip excitation).

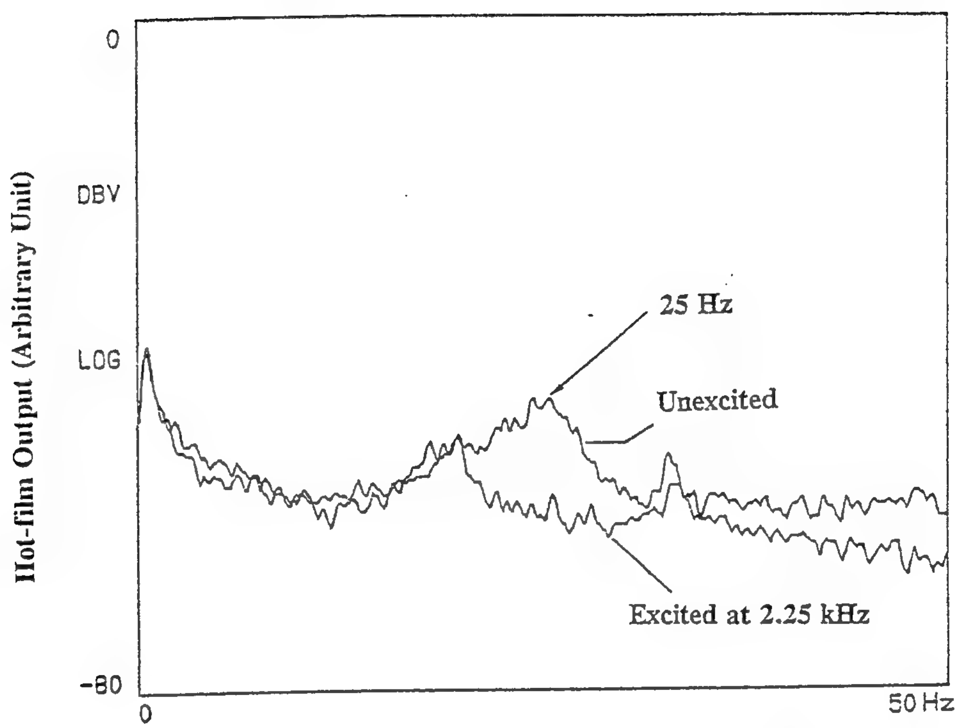
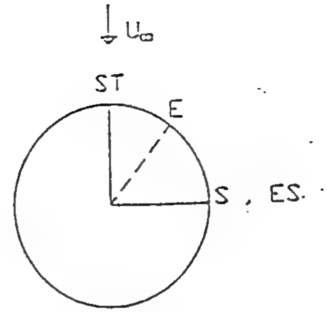
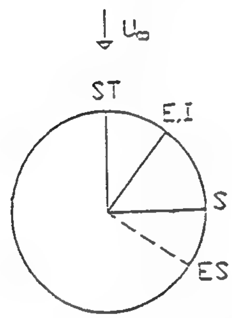


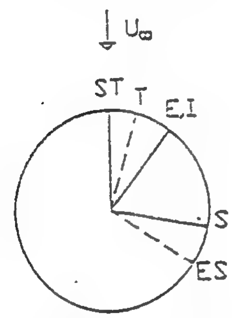
Figure 9. Velocity spectra of cylinder wake under unexcited and excited states. Prominent peak at 25 Hz under unexcited flow conditions. $f_a = 2.25$ kHz. $Re_d = 1.5 \times 10^5$.
Location of excitation : $\Theta = 72°\text{-}74°$.
Measurement location : $\Theta = 110°$, y = 10-mm.



a) Low-Re_d; Stable Laminar Flow



b) Higher Re_d; Transitional Flow

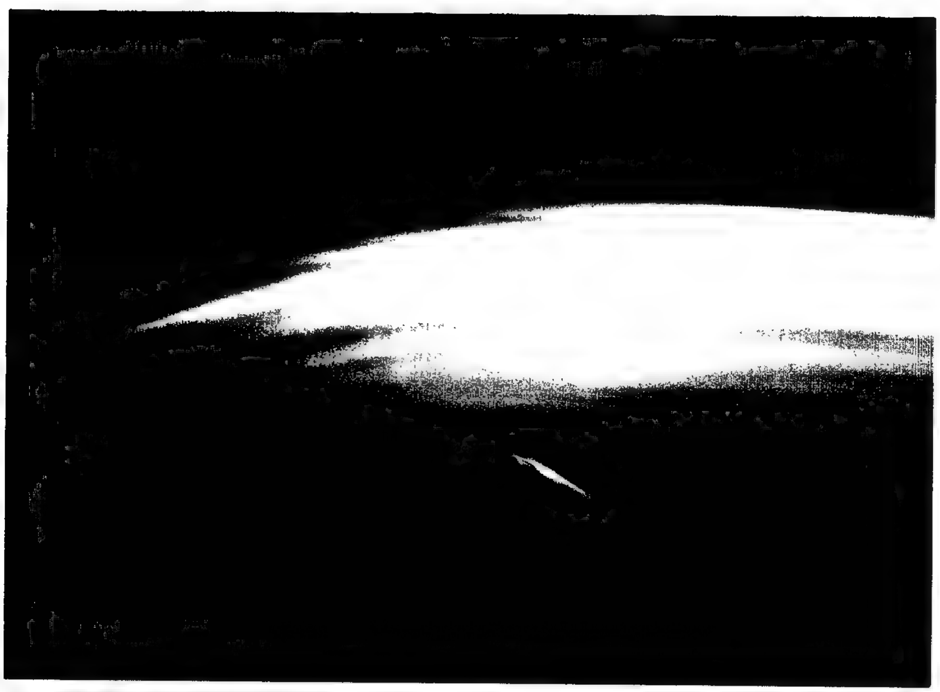


c) Transitional flow tripped at T
to become turbulent

ST - Mean Stagnation Point
I - Instability Point
S - Mean Separation Point (Unexcited)
ES - Mean Separation Point (Excited)
E - Point of Excitation
T - Point of Tripping

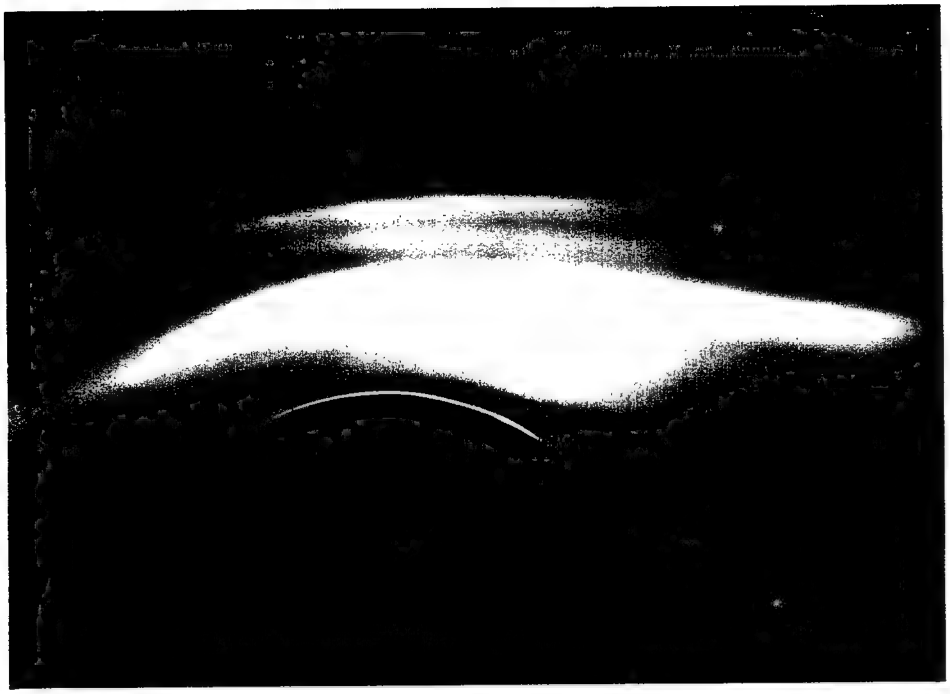
Figure 10. Explanation of flow-acoustic interaction process under different flow and excitation conditions.

(a)



(b)

PLATE 1. $Re_d=1.5X10^5$.(a) No tripping, unexcited.(b)No tripping, excited.



(a)

(b)

PLATE 2. $Re_d=1.5X10^5$.Tripped flow.(a)Unexcited.(b)Excited.

IX. APPENDIX

Copies of three key conference papers resulting from this work.

AIAA 94-0183
CONTROLLING UNSTEADY SEPARATION WITH ACOUSTIC ACTIVE SURFACES

Sumon K. Sinha and Dipankar Pal
The University of Mississippi
University, MS

32nd Aerospace Sciences Meeting & Exhibit
January 10-13, 1994 / Reno, NV

CONTROLLING UNSTEADY SEPARATION WITH ACOUSTIC ACTIVE SURFACES

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University, Mississippi

ABSTRACT

An acoustic active surface, consisting of an array of strip shaped acoustic transducers, has been used to control the unsteady separating flow over a circular cylinder. The acoustic radiation from the strips was found to modify the nonlinear amplification of small disturbances during the boundary layer transition process. This resulted in the reduction in velocity fluctuations, a reduction of the vortex shedding amplitude, a reduction in mean drag, and generation of time averaged lift.

NOMENCLATURE :

C_L = Lift coefficient
= $2L/(\rho U_\infty^2)$
C_p = Pressure coefficient
= $(p-p_\infty)/0.5\rho U_\infty^2$
d = Diameter of the cylinder = 152 mm
f_a = Acoustic excitation frequency
f_s = Vortex shedding frequency
L = Lift force
p = Surface static pressure
p_∞ = Upstream static pressure
Re_d = Reynolds Number based on d = $U_\infty d/\nu$
SPL = Sound pressure level (dB)
St_f = Strouhal Number based on excitation frequency
T_i = Freestream turbulence intensity
= $(u'^2)^{0.5}/U_\infty$ = .30 %
U_∞ = Upstream velocity
U_m = Streamwise mean velocity
u' = Streamwise velocity fluctuation
v' = Normal velocity fluctuation
y = Radial distance measured from cylinder surface
ν = Fluid kinematic viscosity
Θ = Angular position from geometric forward stagnation point

INTRODUCTION :

Controlling unsteady flow separation is of great importance in improving the performance of rotodynamic devices like helicopter rotor blades and axial compressor blades. When the attached flow separates, a loss in lift usually follows. However, unlike flow over fixed lifting surfaces, the separation and resulting stall patterns in these cases are unsteady, and usually more complicated (e.g. dynamic stall on rotor blades and rotating stall on compressor blades). One method to resolve this problem is to use an array of individually controllable acoustic exciters in a sensor-actuator feedback loop[1]. A similar technique using microphones as sensors and wall-suction as the actuation mechanism has recently been used for controlling boundary layer transition on a flat plate[2]. Although several actuation mechanisms[3], ranging from oscillating flaps to jet vortex generators, can be used to control flow separation, the mechanical complexity of these devices often make them impractical for rotor blades and compressor blades. Acoustic transducers can be extremely simple and robust in construction, and usually do not need complicated mechanisms for actuation. This makes them attractive for the applications cited above.

Experimental observations of Ahuja and co-workers[4,5] suggested the possibility of using external and internal acoustic excitation for deterring turbulent boundary layer separation over an airfoil. Zaman and McKinzie[6], and Zaman[7] studied the effect of small amplitude external acoustic excitation on low Reynolds number separating flows over airfoils. Since internal excitation (i.e. sound emanating from within the body) was found to be more energy efficient, Hsiao et al.[8] used a speaker-type acoustic source to study lift enhancement and drag reduction in flows over circular cylinders and airfoils. Sound from a large speaker was piped into the model. It subsequently emanated sound through a slot on the surface. Though the effect of internal acoustic excitation appeared to be beneficial in separation control, experimental investigations of Williams et al.[9] suggested that the interaction mechanism in an acoustic speaker-excited separating flow is primarily mechanical in nature because of the relatively large

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displacements of the acoustic source. This observation was later verified by the present authors[10,11]. In order to alleviate the problem of mechanical perturbation, which requires much higher energy in the form of periodic suction and blowing, an improved acoustic transducer was constructed. This transducer behaves as a line source of acoustic radiation and does not mechanically perturb the flow. In this paper, the term "acoustic active surface" refers to an array of such line sources. This paper focusses on the interaction of this two-dimensional perturbation with a nominally two-dimensional unsteady separating flow.

EXPERIMENTAL FACILITY :

Unsteady separating flow over a circular cylinder was chosen as the test flow. A 152-mm diameter cylinder was placed in crossflow in a 600-mm x 600-mm test section of a subsonic wind-tunnel. An acoustic absorber section and a 180° bend isolated all fan noise from the test-section of the tunnel at frequencies ranging from 10 kHz down to 5 Hz. The flow Reynolds number (Re_d) was varied from 0.5×10^5 to 1.7×10^5. The turbulence intensity (Ti) inside the test-section was found to be about 0.3% at these Reynolds numbers. A schematic of the experimental setup is shown in Figure 1(a).

An "acoustic active surface"[1] consisting of an array of thin strip-shaped (i.e. 1.6-mm in the streamwise direction and 500-mm along the cylinder span) acoustic transducers, was flush mounted onto the upper surface of the cylinder (Figure 1(b).). The strips were oriented parallel to the cylinder axis. Each strip in this configuration could be individually energized by a sinusoidal signal generator. Additionally, each strip in the above mentioned array was also designed to be used as a sensor for measuring wall pressure fluctuations, resulting out of the flow of air over the exposed surface of the transducer. The surface displacements of the transducer elements, when excited sinusoidally (at 20 volts amplitude for this study) were found to be very small (in the order of 10^{-3}-mm, as measured by laser-Doppler vibrometer). This corresponded to a maximum normal surface velocity of about 15 mm/s. This was about three orders of magnitude lower compared to the freestream velocity. Therefore, the direct transfer of momentum due to wall velocity, such as effects similar to periodic bleeding of air, or wall compliance effects, could be ignored. The bleed velocities at the slot of the acoustic speaker type exciter used by the authors in a previous study[11] needed to be around 8.0 m/s; comparable to the oncoming freestream velocities (e.g. 5-15 m/s) for effective control. Lower bleed velocities did not achieve the same degree of control. Proprietary considerations prevent the authors from disclosing pertinent constructional details of the transducers.

A single component hot-film probe was used to measure the mean and fluctuation velocities (U_m, u'_{rms}, and v'_{rms}) at various points; close to the acoustic exciters, in the separated shear layer, and inside the attached boundary layer. The hot film system had an uncertainty of ± 6 cm/s (95% confidence level)[12] for velocities in the range of 5 to 30 m/s. A two component hot film probe was used to measure velocities inside the cylinder wake.

Additionally, a differential pressure transducer (SETRA Model 264), communicating sequentially with surface mounted static-pressure taps, was used to detect changes in the mean (i.e. time-averaged) surface static pressures resulting from the acoustic excitation. The time-averaged pressures had an uncertainty of ± 1.432 Pa in 75 Pa within a 95% confidence level[12]. The frequency response and the sound pressure level (SPL) of the acoustic excitation were measured with a 1/4 inch (6-mm) B & K condenser microphone. The SPL at the surface was kept constant at 75 dB. Lower SPL values were not effective in separation control. The frequency responses of three representative transducer strips (in the streamwise direction) are shown in Figure 2. The variation in response along the length (i.e. along the cylinder span) of each strip was within 7%.

RESULTS AND DISCUSSIONS :

Pure acoustic radiation (i.e. in the absence of mechanical unsteadiness like blowing or suction) from the acoustic active surface was found to be beneficial in delaying unsteady separation over the circular cylinder. The transducer strips were designed so as to introduce nominally two-dimensional disturbances in the absence of large velocity perturbations. For the frequencies used in this study, the acoustic wavelengths were significantly larger than the width of the strips. Hence the strips have been assumed to behave as line sources. The interaction mechanisms between the acoustic disturbance and the near-separation boundary layer flow is complex. Additional complications arise out of the three-dimensionality[13] in the separated flow. However, some interesting changes in the flowfield variables could be measured with consistent accuracy and repeatability so as to permit a qualitative study of the separation point movement.

The optimum Strouhal number (St_f) for controlling

the separating boundary layer flow with acoustic waves emanating from the surface was found to be about 23. This is an order of magnitude higher than those reported with internal periodic bleeding[4,5,8]; thereby suggesting a different flow-acoustic interaction mechanism. The strips were excited one at a time, and changes in mean surface static pressures were noted. Once the optimum angular location for the point of excitation was determined, the effect of driving multiple strips (in phase) centered around this point was determined. For $Re_d = 1.54 \times 10^5$, largest changes in mean static pressures were observed when two adjacent strips, spanning the region between 72° and 74° from the mean forward stagnation point, were excited at 2.25 kHz. The selection of the excitation frequency (f_e) at this Re_d was based on the information obtained from one of the transducer strips acting as a wall pressure fluctuation sensor. Figures 3(a) and 3(b) show the spectra of velocity and wall pressure fluctuation immediately downstream of the excitation point at this Re_d, in absence of any internal excitation. The pressure spectrum (at $\Theta = 78°$, i.e. near the time-averaged mean separation point) shows a peak at 2.25 kHz. It is important to note that the transducers did not have any resonances at this frequency (See frequency response , Figure 2.). Therefore, this frequency indicates a flow-induced instability near the separation point. It is interesting to note that this peak does not show up in the velocity spectrum (Figure 3(a).).

Changes in mean lift and drag :

Figure 4 shows the changes in mean surface pressures as a result of exciting the two strips between 72° and 74°. A mean coefficient of lift (C_L) of 0.15 was observed when no acoustic excitation was used. The mean C_L on a circular cylinder should have been zero under perfect experimental conditions, but the presence of the acoustic active surface, though mounted flush on the cylinder, changed the steady pressure distribution on the cylinder to a certain extent. This change (i.e. under unexcited conditions) can be brought about by the additional compliance or roughness introduced by the active surface, since the active surface was mounted on one side of the cylinder. The design of the active surface allowed the surface compliance to be varied artificially. However, changing the compliance did not change the flow. Hence it was concluded that the change in time-averaged pressure distribution on one side of the cylinder was primarily due to surface roughness. Visual inspection of the surface showed some minor irregularities in the order of 0.25 to 0.5-mm. When acoustic excitation was used to perturb the flow (f_e=2.25 kHz, at $\Theta = 72°$-74°), the net lift force on the cylinder increased, and the corresponding value of C_L was 0.47. A corresponding decrease in form drag of 12.4% was also noted. Lift and drag forces were estimated by numerical integration of the time-averaged static pressure distribution data over the entire cylinder.

Changes in velocity fluctuation spectra :

Hot-film measurements close to the cylinder surface, both upstream and downstream of the optimum excitation region, showed an increase in the time-averaged streamwise mean velocities (U_m) when the strips were energized. The corresponding fluctuating components of velocity (u'_{rms} and v'_{rms}) decreased (Figures 5(a). and 5(b).). Figure 5(a) shows the time-averaged spectra of u' in the unexcited and excited boundary layers, at $\Theta = 74°$ from forward stagnation (i.e. pre-separation, even under unexcited conditions). Figure 5(b) shows the same but at a location where the unexcited boundary layer has already separated ($\Theta = 82°$).

Figure 6 shows the distribution of mean and fluctuation velocities close to the surface (y = 1 mm for all measuring stations) for the flow at $Re_d = 1.5 \times 10^5$ and clearly shows the delay of separation brought about by pure acoustic excitation. The time-averaged separation point was close to $\Theta = 78°$ and, under acoustic excitation, moved downstream to $\Theta = 106°$ from the forward stagnation point. The velocity fluctuations decreased as a result of excitation. Additionally, the location where the largest fluctuations occurred receded to $\Theta = 106°$ from $\Theta = 80°$ as a result of delayed separation (Figure 6).

Two-component velocity measurements were performed close to the cylinder surface inside the wake region using the two-component hot-film probe. This assumes that the spanwise components of velocities (w) are significantly smaller than the other two components (u and v). Measurements showed that both streamwise and normal components of velocity increase as a result of acoustic perturbation. Two-component velocity measurements also showed that velocity fluctuations near the vortex-shedding frequency (around 25 Hz at $Re_d = 1.54 \times 10^5$) decreased as a result of acoustic excitation. Figure 7 shows the velocity spectra, measured by the one of the two velocity sensors, inside the cylinder wake ($\Theta = 110°$ and y = 10-mm). The unexcited spectrum shows prominent peaks near 25 Hz. Under acoustic excitation (f_e = 2.25 kHz and Θ = 72°-74°), the amplitude of these peaks decrease remarkably. It suggests that the vortex-shedding velocity amplitude is reduced under excitation. Therefore, the movement of the separation point in each cycle of oscillation decreases too.

Since the flow Reynolds number, at which the effect of acoustic excitation was studied, was very close to the transitional Reynolds number for the cylinder, it was apprehended that the acoustic disturbance actually facilitates the laminar-turbulent transition process. To study the effect of acoustic excitation on a turbulent boundary layer, the flow over the cylinder was tripped at $\Theta = 34°$-$36°$ using a sand-paper trip. To ensure that the flow had actually become turbulent, single-element hot-film probe measurements were carried out very close to the cylinder upper surface. Figure 8 shows the distribution of mean and fluctuation velocities close to the surface (y = 1 mm for all measuring stations) for the tripped flow at $Re_d = 1.5 \times 10^5$. Since the separation point was expected to move downstream as a result of tripping, the active surface was positioned at 85°-115° so that the acoustic excitation was applied close to the separation point. The experiment showed that exciting the flow at $\Theta = 92°$-$94°$ did not produce perceptible changes in either the mean or the fluctuation velocities. In order to find the optimum point of excitation for the tripped boundary layer, the point of excitation was moved back to $\Theta = 72°$-$74°$ keeping the tripping location unchanged. A significant change in the mean static pressure distribution was now observed (Figure 9). The nature of pressure change in this case was different than that obtained by exciting the undisturbed (or, untripped) boundary layer. Exciting the tripped boundary layer produced an overall change in the surface pressure distribution in the cylinder wake ($\Theta = 95°$ to $\Theta = 300°$). Numerical integration of the pressure distributions under two different conditions (unexcited and acoustically excited) indicated that the average lift coefficient (C_L) changed from 0.33 to 0.54 under excitation. Also, the form-drag force was reduced by 20.2% due to the change in surface pressure distribution in the wake region. Thus, the acoustic excitation seems to have a synergistic effect in controlling the tripped separating flow.

CONCLUSIONS AND RECOMMENDATIONS :

In this experimental study, an attempt has been made to characterize the flow-acoustic interaction in flow separation control. Experimental observations lead to the conclusion that "pure" acoustic excitation can be successfully used to delay unsteady flow separation over convex boundaries. Also, the capabilities and limitations of the two-dimensional, pure acoustic excitation in controlling unsteady separation could be investigated in detail.

A Mechanistic Explanation of the flow-acoustic interaction process is given in Figure 10. When the flow Reynolds number is very low, naturally occurring disturbances in the boundary layer are damped out. Consequently, laminar separation occurs. Small amplitude perturbations, such as the acoustic radiation from the strips, are not effective in this region (Figure 10(a).) since they are damped by the flow. As the Reynolds number is increased, the point at which small instabilities begin to amplify moves upstream of the separation point. However, the distance between the instability point and separation point is still too small for naturally occurring disturbances to amplify sufficiently. If a small acoustic disturbance of the appropriate frequency is introduced close to the instability point (around 72°-74° at $Re_d = 1.54 \times 10^5$ for the present case), it can be amplified sufficiently to change the velocity profile. This moves the separation point further downstream. Additionally, a significant effect is produced only if the amplitude of the acoustic perturbation is higher than the naturally occurring disturbances. For the present experiments no changes were observed when the SPL was less than 70 dB. Also, significantly higher SPL values (e.g. 100 dB) did not produce noticeable improvement. If the acoustic disturbances are introduced further upstream, they get attenuated by the flow to levels comparable to the ambient noise, and are therefore ineffective (Figure 10(b).). If they are introduced downstream of the instability point, once again they are not as effective since they have to compete with higher (amplified) ambient disturbances. Also, the introduced disturbances do not get a chance to amplify adequately.

Tripping the flow with a sandpaper amounts to introducing large-amplitude disturbances. Even after being partially damped by the flow upstream to the instability point, the residual disturbances can amplify to promote transition and delay separation. In order to compete effectively with these relatively large-amplitude disturbances, the small amplitude disturbances have to be introduced very close to the instability point. The net result is a modification of the non-linear amplification process. This shows up in the velocity spectrum of the wake. It is believed that second and higher order effects similar to acoustic streaming play a vital role during this process.

The acoustic wavelength in air at the optimum excitation frequency of 2.25 kHz is about 145-mm. This was not close to any of the possible resonant modes in the wind-tunnel. However, this wavelength was significantly larger than the maximum boundary layer thickness (about 5-mm). Hence the acoustic disturbances perturbed the freestream flow as well (i.e. similar to external acoustic

excitation). Sinha and Pal discussed the possibility of triggering unstable Tollmien-Schlichting (TS) waves as a result of acoustic excitation, because the Re_d values used were close to the critical values for the cylinder. In a recent numerical study, Frendi et al.[14] investigated the interaction of planar acoustic waves emanating from a section of a flat plate with a supersonic boundary layer over it. Their investigations have revealed that pressure fluctuations in the boundary layer are affected most by sound at frequencies which are submultiples of the lowest unstable TS frequency, and correspond to one of the natural frequencies of the plate. The acoustic waves were also found to introduce inflections in the boundary layer velocity profile and enhance the movement of vorticity from the wall into the flow. Although the present flow is subsonic, the mechanisms for promoting TS-instabilities are probably similar. The peak in the pressure fluctuation spectrum probably corresponds to a submultiple of the TS-frequency.

The acoustic strip-shaped transducer reduced velocity fluctuations near the wall. This reduction at practically all frequencies can be attributed to a flow of velocity-fluctuation energy towards pressure-fluctuation energy. When the flow is excited, pressure fluctuations are found to increase at the excitation frequency. However, it is still a speculation, which needs to be verified. Additionally, the changes in mean static pressure on the surface of the cylinder indicated lift enhancement and drag reduction. Since large-scale velocity and pressure fluctuations due to vortex-shedding are superposed on small-scale instabilities, the phase relation of the two is of great significance (Ffowcs Williams and Zhao[15], Farabee and Casarella[16]). The transducer array can be used to achieve phased-array excitation using a time-delay signal. Proper filtering of the input signals from the velocity and pressure sensors is required to achieve accurate measurement of the phase relationship. The pressure fluctuations sensed by the individual strips contain a wide range of frequencies, and further signal processing will be required in order to track the separation point more accurately.

The multiple-strip excitation suggests that a phased oscillation is required to introduce small-scale vortical structures into the separating flow so that transition can be achieved easily. It is also important to select a proper location for excitation, such that the relatively small-strength perturbation can grow adequately inside the attached boundary layer so as to modify the naturally occurring flow disturbances. Figure 8. shows that perturbing the flow at a point, where the flow fluctuations are already sufficiently high, does not change the flow character significantly.

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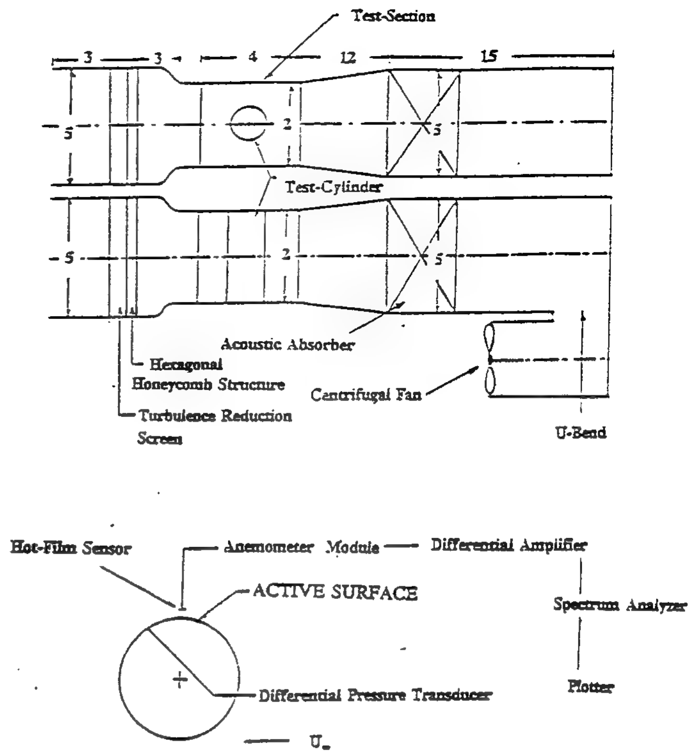

Figure 1(a). Construction details of the wind-tunnel testing facility. All dimensions in ft.

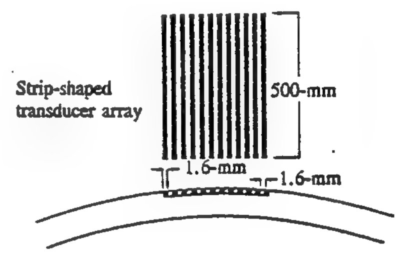

Figure 1(b). Orientation of strip-shaped acoustic transducer array on the cylinder surface.

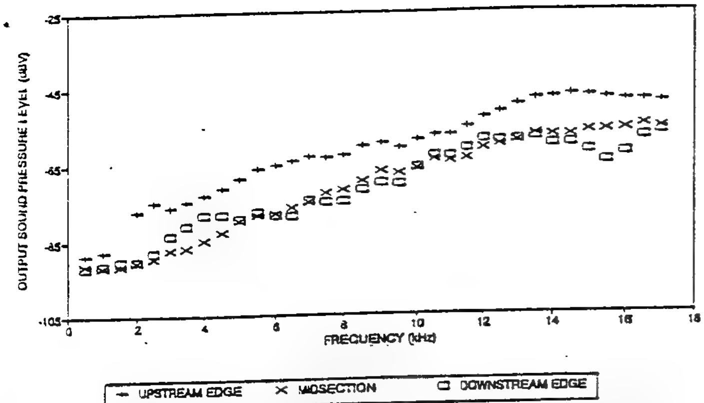

Figure 2. Acoustic frequency response of three different strip-shaped transducers (upstream edge, midsection and downstream edge) on the acoustically active surface.

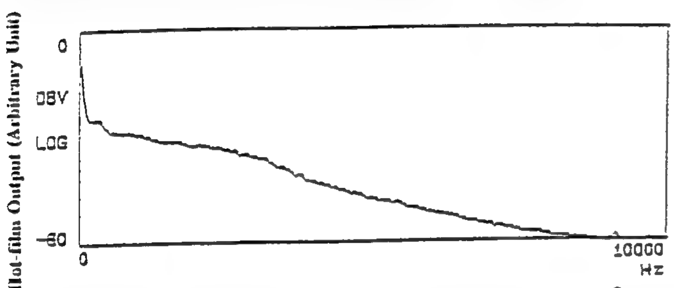

Figure 3(a). Time-averaged velocity spectrum of pre-separation boundary layer in the absence of acoustic excitation. $Re_d = 1.5 \times 10^5$. Measurement location : $\Theta = 78°$, y = 5-mm.

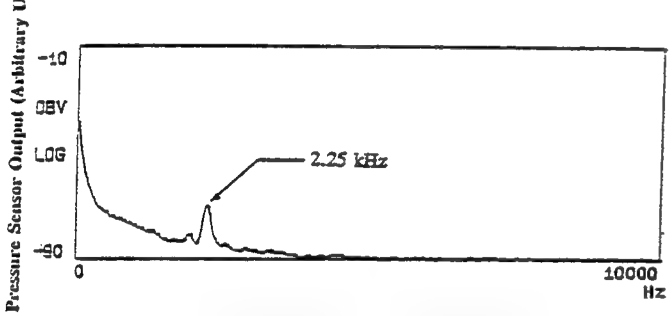

Figure 3(b). Time-averaged surface pressure spectrum of pre-separation boundary layer in the absence of acoustic excitation.

$Re_d = 1.5 \times 10^5$. Measurement location : $\Theta = 78°$.

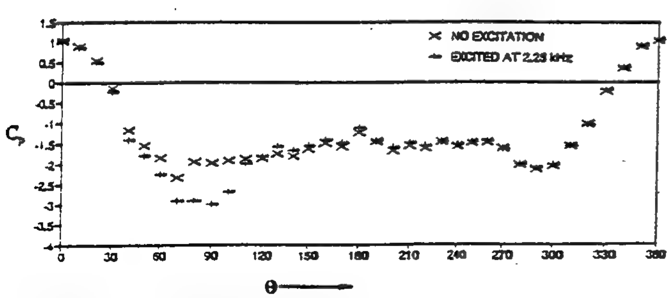

Figure 4. Surface static pressure distribution (unexcited and excited flow states). $Re_d = 1.5 \times 10^5$. $f_e = 2.25$ kHz. Location of excitation : $\Theta = 72°$-$74°$ (multiple strip excitation).

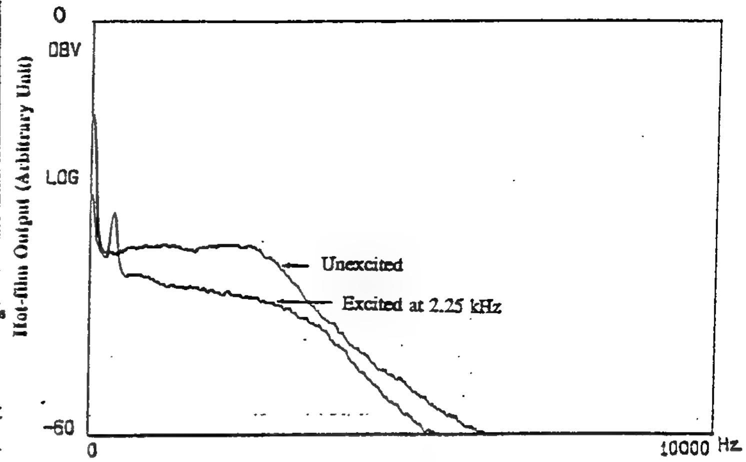

Figure 5(a). Time-averaged velocity spectra of pre-separation boundary layer. $Re_d = 1.5 \times 10^5$.
$f_e = 2.25$ kHz. Excitation location : $\Theta = 72°$-$74°$ (multiple strip excitation). Measurement location :
$\Theta = 74°$, y = 2-mm.

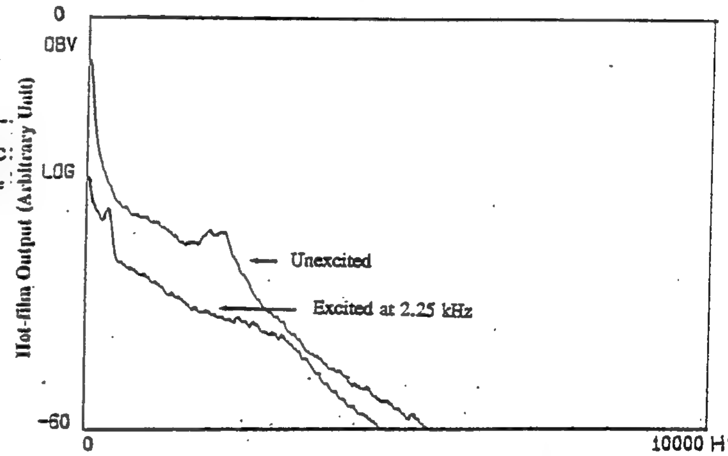

Figure 5(b). Time averaged velocity spectra of post-separation shear layer. $Re_d = 1.5 \times 10^5$. $f_e = 2.25$ kHz. Excitation location : $\Theta = 72°$-$74°$ (multiple strip excitation). Measurement location : $\Theta = 82°$, y = 8-mm.

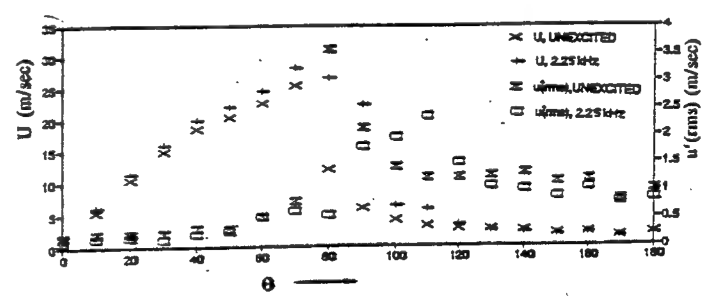

Figure 6. Distribution of time-averaged mean and fluctuation velocities close to the cylinder surface.
y = 1-mm for all measurement locations.
$Re_d = 1.5 \times 10^5$. and $f_e = 2.25$ kHz.
Excitation location : $\Theta = 72°$-$74°$ (multiple strip excitation). Measurement Location : $\Theta = 90°$, y = 5-mm.

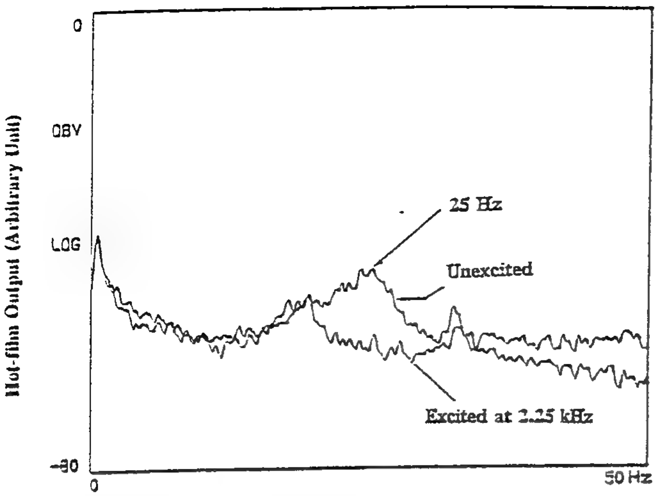

Figure 7. Velocity spectra of cylinder wake under unexcited and excited states. Prominent peak at 25 Hz under unexcited flow conditions. f_s = 2.25 kHz, Re_d = 1.5 x 10^5. Location of excitation : Θ = 72°-74°. Measurement location : Θ = 110°, y = 10-mm.

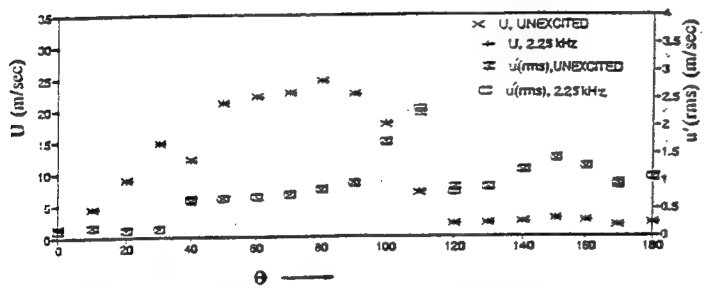

Figure 8. Distribution of time-averaged mean and fluctuation velocities close to the cylinder surface. y = 1-mm for all measurement locations. Re_d = 1.5 x 10^5. f_s = 2.25 kHz. Artificial flow tripping at Θ = 35°. Excitation location : Θ = 92°-94° (multiple strip excitation).

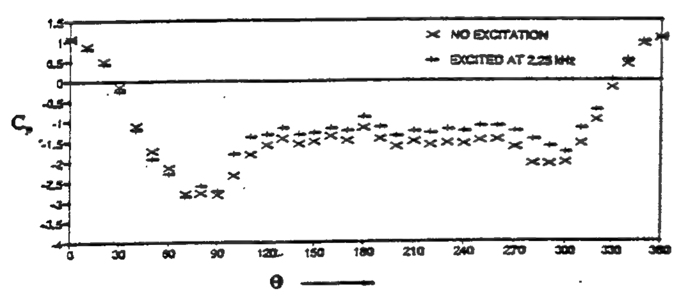

Figure 9. Surface static pressure distribution (unexcited and excited flow states). Re_d = 1.5 x 10^5. f_s = 2.25 kHz. Artificial flow tripping at Θ = 35°. Location of excitation : Θ = 72°-74° (multiple strip excitation).

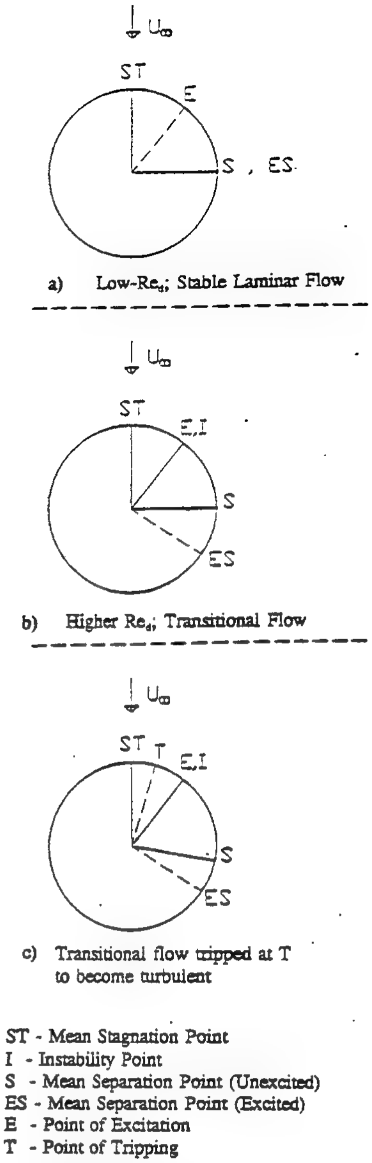

Figure 10. Explanation of flow-acoustic interaction process under different flow and excitation conditions.

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OPTIMIZING THE USE OF ACOUSTIC PERTURBATION TO CONTROL UNSTEADY BOUNDARY LAYER SEPARATION

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ABSTRACT

Unsteady separating flow over a 168 mm diameter circular cylinder has been acoustically perturbed by (1) a speaker mounted inside the cylinder and blowing through a rectangular slot on the surface of the cylinder; and by (2) a piezo-electric acoustic transducer mounted flush with the surface. The first mode of excitation was most effective at about 450-600 Hz for a flow Reynolds number range of 5×10^4-1.7×10^5, based on maximum changes in the pressure distribution on the surface of the cylinder. Surface pressure changes were most pronounced at about 5.5-7.0 kHz for a Reynolds number range of 1.4×10^5-1.7×10^5 when the piezo-electric transducer was used. The first mode of excitation subjected the boundary layer to acoustic radiation along with significant blowing and suction through the wall. Enhanced mixing due to suction and blowing is absent in the second mode.

1. NOMENCLATURE

c = Velocity of sound in fluid
C_p = Pressure coefficient = $(p-p_\infty)/0.5\rho U_\infty^2$
d = Diameter of the cylinder = 168 mm
f_a = Acoustic excitation frequency
f_s = Vortex shedding frequency
h = Height of wind-tunnel test section = 60 cm
l = Length of the cylinder = 60 cm
p = Surface static pressure
p_∞ = Upstream static pressure
q = Aspect Ratio = l/d = 3.57
Re_d = Reynolds Number based on cylinder diameter = $U_\infty d/\nu$
S = Blockage ratio = d/h = 0.28
St_f = Strouhal Number based on excitation frequency
T_i = Freestream turbulence intensity = $(\overline{u'^2})^{0.5}/U_\infty$ = .30 %
U_∞ = Upstream velocity
U_m = Streamwise mean velocity
u' = Streamwise velocity fluctuation
v' = Normal velocity fluctuation
x = Streamwise distance measured from cylinder top
y = radial distance measured from cylinder surface
ρ = Fluid density
ν = Fluid kinematic viscosity
Θ = Angular position from geometric forward stagnation

point
λ = Wavelength of sound

2. INTRODUCTION

Numerous examples of unsteady boundary layer separation can be found in engineering, ranging from dynamic stall over helicopter rotors and wind-turbine blades, to rotating stall in axial compressors. Usually the effects of flow separation are detrimental to performance, and several techniques for controlling flow separation have been investigated [5]. Most of these techniques, such as riblets or wall-mounted wing type vortex generators, have to be specifically tailored to the flow, especially with respect to the spatial location of the separation point. This implies that these devices do not operate under optimal conditions when the point of separation moves (i.e. unsteady separation). On the other hand, devices designed to track the separation point, and apply the appropriate control response at the spatial location most effective for preventing or delaying separation, can be extremely complex mechanically. One method to resolve this problem is to use an array of individually controllable acoustic exciters in a sensor-actuator feedback loop [12]. This approach however is still unproven; although the effectiveness of the feedback control concept, using microphones as sensors and wall-suction as the actuation mechanism, has recently been used for controlling boundary layer transition on a flat plate [9].

Experimental investigations have revealed that acoustic disturbances of suitable frequencies and amplitudes can successfully deter the process of steady and unsteady separation [5,7,10,14-16]. Acoustic disturbances are thought to enhance mixing inside the separated shear layer, thereby increasing the momentum of the fluid close to the wall. The effect of small- amplitude acoustic excitation on the separating flow over airfoils, at low angles of attack, and low chordal Reynolds numbers, was studied by Zaman et al. [14]. The gain in aerodynamic lift was found to depend on the frequency and amplitude of the acoustic perturbation. This study [14] was subsequently extended to estimate the acoustic frequencies and amplitudes most effective in controlling the post-stalled flows of these airfoils [15,16].

It is believed that acoustic perturbation at the correct frequency enhances mixing by exciting instabilities in the separated shear layer, or perhaps in the unseparated boundary layer. However, the exact mechanisms have yet to be correctly identified, since the optimum excitation frequency, expressed as a Strouhal number, has been found to vary by more than an order of magnitude for seemingly identical flow set-ups [16]. Furthermore, these studies were carried out at relatively low chordal Reynolds numbers, and therefore may not truly represent the flow-acoustic interaction inside the separated shear layer of high Reynolds number flows typical of most practical applications. Additionally, the effect of the design of the acoustic exciter is not yet very clear.

A measure of the effectiveness of any separation control technique is the ratio of the energy saved (e.g. due to drag reduction) to the energy required to control it. For acoustic excitation, this depends on the effectiveness of perturbing naturally occurring flow instabilities. For example, disturbances emanating from the surface over which the flow occurs (i.e. internal excitation) have been found to be more effective than those from acoustic sources outside the boundary layer (i.e. external excitation) [7]. In order to optimize the use of acoustic perturbation for separation control, an understanding of the acoustic-flow interaction mechanisms and their relationships to actuator design is crucial. The purpose of this paper is to reveal recent experimental results from an ongoing investigation aimed at resolving some of these issues. The flow selected for this purpose is the unsteady flow over a circular cylinder.

3. EXPERIMENTAL FACILITY

A 168-mm diameter circular cylinder was placed in crossflow in a 600-mm x 600-mm test section of a subsonic wind tunnel. The aspect ratio (q) of the cylinder was 3.57 and the blockage ratio (S) was 0.28 (see Figure 1.). The freestream turbulence intensity (T_i) for the Reynolds number (Re_d) range of $0.5 \times 10^5 - 1.7 \times 10^5$ was about 0.3%. Two

different modes of acoustic excitation (Cases I and II) were studied. In the first case a 50-mm diameter speaker was mounted under the solid boundary of the cylinder. The speaker communicated with the external flow over the cylinder through a 2-mm wide and 25-mm long spanwise rectangular slot on the surface of the cylinder. The speaker was driven by a sinusoidal signal generator through a power amplifier. Following the findings of Hsiao et al. [7], who used a similar approach to successfully control flow separation, the angular location of the slot was close to the unperturbed mean separation point of the flow. For similar experimental conditions (i.e. similar Reynolds numbers, aspect ratios, freestream turbulence intensity etc.), Achenbach [1] estimated the angular position of the separation point as 78-90 degrees from the forward geometric stagnation point. The corresponding minimum surface-pressure points were found to lie between 70-80 degrees from the stagnation point. The acoustic frequency response of the speaker-slot system, when driven with a 10 volt peak-to-peak sinusoidal signal, is shown in Figure 2.1. In order to alleviate problems due to the acoustic resonant characteristics of the excitation system, the electrical input to the speaker was controlled to hold the sound pressure level at the slot exit constant at 115 db for all frequencies of excitation considered. This however does not control the flow of the air through the slot (Williams et. al. [13]). The Reynolds number (Re_d) was varied from 57,300 to 166,000 by varying the wind-tunnel fan speed. A single component hot-film probe was used to measure velocity fluctuations in the separated shear layer. The hot-film system had an uncertainty of ±6 cm/s (95% confidence level)[1] for velocity magnitudes in the range of 5 to 30 m/s. Additionally, a pressure transducer (Setra Model 264), communicating sequentially with several static-pressure taps, was used to detect changes in mean (i.e. time averaged) static pressure on the cylinder surface resulting from the acoustic excitation. The output of the pressure transducer was averaged over 30 seconds so as to smooth out the effects of the slowest fluctuations (typically, the vortex shedding frequencies which were about 10 Hz). The averaged pressure had an uncertainty of ±1.432 Pa within a 95% confidence level.

In the second case the speaker was replaced with a 25-mm diameter piezo-electric transducer, mounted flush with the cylinder surface and exposed to the flow. The actuator radiated sound when driven with the signal generator and amplifier. This transducer had a resonant frequency of 3.2 KHz under free (non-mounted) conditions. The frequency response of the mounted piezo-electric transducer was recorded using a 1/4 inch B & K condenser microphone (Cartridge type 4147). The manufacturer-calibrated B & K microphone had a flat frequency response till 20 KHz. The most prominent resonant frequency of the transducer, increased to 6 kHz after being mounted on the cylinder surface (Figure 2.2).

In addition to the pressure transducer and the hot-film probe, a miniature microphone (KNOWLES Model BW-1789) was also flush-mounted on the cylinder surface, immediately downstream of the piezo-electric acoustic transducer. Figure 2.2 shows that the responses of both microphones (Knowles and B & K) are similar when excited with the mounted piezo transducer in the 1 to 40 kHz range; the Knowles microphone being more sensitive.

4. RESULTS AND DISCUSSION

Experiments with both exciters showed evidence of interaction with the flow. There were however significant differences. These are described below.

Case I: (Speaker blowing through slot)

Figure 3.1 shows a typical averaged frequency spectrum of the velocity, at $Re_d = 0.67 \times 10^5$. This was measured with the hot-film sensor (axis parallel to the axis of the cylinder) slightly downstream of the separation point in absence of any acoustic excitation. The first peak at 9.8 Hz corresponds to f_s, the vortex-shedding frequency of the cylinder. The next peak (which is marked in the figure) is thought to correspond to the instability frequency of the separated shear layer, since this and other higher frequency peaks do not correspond to the harmonics of the shedding frequency f_s. Additionally, various tunnel resonant frequencies (e.g. longitudinal, transverse etc.) were calculated and found not to coincide with the two higher peak frequencies (387.5 Hz and 570 Hz). The magnitudes of these peaks compared to

the background were found to reduce with increasing Reynolds numbers (Compare Figures 3.1. and 7).

The speaker was then energized, and the largest change in mean static pressures was observed for f_a = 412.5 Hz. The interaction between the imposed perturbation (at 412.5 Hz) and the separated shear layer suggests a typical lock-in frequency (which is close but slightly different from the supposed instability frequency) for each value of Re_d. Figure 3.2 shows the averaged frequency spectrum when the flow is excited at the corresponding lock-in frequency. No such lock-in phenomenon was observed when the flow was excited at or around 570 Hz (the third peak in Figure 3.1). The relationship between the lock-in or optimum excitation frequency, and Re_d is distinctly different for low (Re_d= 5,000 to 20,000 ; laminar) versus high (Re_d= 60,000 to 200,000 ; transitional to turbulent in the present setup) values, as shown in Figure 4.

The measurement of time-averaged static pressures on the surface of the cylinder showed that the minimum pressure point on the cylinder moves downstream as Re_d is increased. Figure 5 shows that a slight change occurs in the mean static pressure distribution when the speaker is energized. The decrease in static pressure due to acoustic excitation is expected to be maximum immediately downstream of the point of excitation. However, no pressure port could be provided in the vicinity of the slot due to the relatively large size of the speaker.

Although at this stage the results appear to be quite encouraging in terms of boundary layer separation control by acoustic excitation, the very fact that direct momentum transfer into the unsteady boundary layer occurs due to periodic suction and blowing of air through the slot, calls for a closer investigation. The root mean squared velocity fluctuation at the slot exit was measured with the hot-film sensor when the speaker was driven between 350 and 750 Hz under no flow conditions. The measured fluctuations (v'_{rms}) were much larger compared to acoustic particle velocities. The acoustic particle velocities were estimated from the acoustic impedance (ρ.c) and pressure fluctuations at the slot exit (measured with the B & K microphone). This in fact implies two perturbation mechanisms; the acoustic pressure fluctuations, and the velocity fluctuations due to alternate blowing and suction through the slot[2], although most investigators [7,10,14-16] do not explicitly acknowledge the second effect.

The acoustic wavelengths λ (i.e. c/f_a), for the optimal values of f_a at which the flow appeared to be receptive to the perturbation, were at least two orders of magnitude higher than the boundary layer thicknesses near separation. Also, the 2- mm wide slot very close the separation point introduces additional disturbances, whose effects cannot be ignored. A study of flow separation control by unsteady bleed techniques (or alternate blowing and suction) by Williams et al. [13] also suggests similar phenomena.

Case II: (Excitation with Piezo-electric transducer)

Since considerable disagreements exist between the results of similar experiments which use sound from speakers to control flow separation [16,17] it was necessary to investigate the phenomenon without using a large speaker as the acoustic source. The piezo-electric transducer used here produced very small displacements under excitation (about 0.0001 mm at its resonant frequency of 6 kHz, as measured with a laser-Doppler vibrometer). This corresponds to a surface velocity of 3.6 mm./sec (approx.). Hence, this effectively eliminated the effect of direct blowing and suction into the boundary layer. Additionally velocities close to the wall, as measured by the hot-film probe, were found to be almost zero under no flow conditions (although thermal anemometry cannot be expected to yield accurate results at near-zero velocities). The only drawback was the relatively large size of the present transducer, compared to the width of the slot in Case I. This limited the scope of estimating the optimal spatial location of the point of excitation, since the movement of the separation-point over a vortex-shedding cycle was less than the diameter (25-mm) of the piezo-electric transducer.

The study of the flow-acoustic wave interaction in this experimental setup

suggests a negative effect on drag reduction due to acoustic perturbation alone. The present results showed that pure acoustic excitation reduces the mean and fluctuating component of fluid velocity inside the shear layer. Figures 6.1, 6.2 and 6.3 show the gain in static pressures as functions of excitation frequencies for three values of Re_d. The pressure transducer measured static pressures at the downstream end of the 25-mm diameter piezo-transducer, whose center was located 80° from stagnation. The hot-film probe was used to measure the mean velocity inside the separated shear layer close to the static pressure measurement location (typically 3-5 mm away from the surface of the cylinder). The decrease in time-averaged local velocity heads ($V^2/2$) is assumed to reflect a corresponding increase in local static pressures. Hence the trends in the two estimates of pressure gains are similar; differences in magnitudes resulting from the rather arbitrary selection of hot-film sensor positions inside the unsteady shear layer.

A range of excitation frequencies was found to be effective for a given value of Re_d. The mid-points of these broad-band frequency ranges were found to increase with Re_d. These frequencies are in the order of several kHz, and therefore have wavelengths in air which are still about an order of magnitude larger compared to the corresponding boundary layer thicknesses. Moreover, these did not match any of the pertinent wind-tunnel resonance frequencies (e.g. longitudinal, transverse, between the cylinder and test-section wall, inside the cylinder etc). It should be pointed out that the piezo-electric transducer did not produce any measurable changes in the flow velocities and pressures when excited at frequencies around 300-700 Hz (i.e. the optimum frequencies in Case I). This is probably due to the poor frequency response of the piezo-transducer at these frequencies (Figure 2.2). Similarly, driving the speaker (Case I) at around 5-7 kHz did not produce appreciable changes in the flow velocities and pressures. The maximum measured wall pressure gain occurred at a Reynolds number of 159,000 when excited at 7 kHz. Figure 7 shows the velocity spectra of the unexcited and excited shear layers at this Reynolds number. The magnitudes of velocity-fluctuations in the shear layer, centered around the respective excitation frequencies, decreased as a result of pure acoustic excitation. Figures 8.1 and 8.2 show the frequency spectra, as obtained from the surface mounted miniature microphone. These show that the pressure fluctuations are enhanced at the excitation frequency and its harmonics, and attenuated for frequencies lower than the excitation frequency.

The contribution of the sound pressure level (SPL) in the process of interaction was also found to be minimal as long as the SPL was above 90 dB. This SPL is characteristic to the design of the transducer and therefore not regarded as an important parameter for the flow-acoustic interaction mechanism.

Figures 9.1 - 9.3 show static-pressure gains on the surface of the cylinder for different angular positions of the transducer. The gains are seen to be maximum when the location of the acoustic source is near the point of mean separation.

5. CONCLUSIONS

Considerable differences have been found in the way different acoustic sources interact with unsteady separating boundary layers. The nature of perturbation effected by a speaker seems to be predominantly mechanical (i.e. blowing and suction) rather than acoustic. When the flow is perturbed by direct momentum transfer due to periodic blowing and suction of air, it enhances mixing inside the separated shear layer and consequently reduces the form drag. Also, an increase in the maximum displacement of the speaker-cone (as a result of increased power input to the speaker) enhances form-drag reduction. For example, the speaker-slot exciter used by Hsiao et al. [7] produced larger pressure gains, although the sound pressure levels used were comparable to the present case. The main difference is that they probably introduced larger bleed velocities since a larger amount of air was displaced by their speaker. Additionally, their speaker was not located directly under the slot, thereby reducing the SPL at the slot for a given bleed rate (compared to the present setup). This supports the observations of Williams et al. [13].

In the present case, when the flow is excited solely by acoustic waves at the appropriate frequency, the form drag on the cylinder surface is found to increase by a very small amount. Moreover, the effect of the flow-acoustic interaction is more pronounced upstream of the point of excitation. A similar increase in drag was found by Kim and Durbin [8], who projected externally generated sound waves on a sphere along the direction of the mean flow. They attributed the increase in drag to a reduction in the separation region, as a result of the separated shear layer converging within a shorter distance behind the sphere.

The large size of the present transducer, prevents the study of localized excitation effects. However, the effect of inaccuracies in locating the center of the transducer can result in significant differences in the maximum pressure gains realized as seen by comparing figures 6.2 and 9.2. Dwyer [2] found multiple zero shear-stress points on the cylinder surface due to the unsteady nature of the separation process. The movement of the separation point along the surface is also affected by excursions of the stagnation point during a typical vortex-shedding cycle. Since large-scale velocity and pressure fluctuations due to vortex-shedding are superposed on small-scale instabilities, the phase relation of the two is of great significance. (Ffowcs Williams and Zhao [4], Farabee and Casarella [3]). Thus, an approach towards optimization will involve tracking the separation point more accurately [12].

Experimental studies, by Higuchi et al. [6] on unsteady flow separation over circular cylinders (at Re_d values comparable to the present case) have shown that three-dimensional coherent flow structures exist along the span of the cylinder. Hence, spanwise variations in instantaneous pressures and velocities need to be considered for implementing localized excitation.

The interaction due to pure acoustic waves is most pronounced within a narrow range of Reynolds numbers in the neighborhood of the laminar-turbulent transition regime for the cylinder. This suggests a possible mechanism in terms of transition promotion. The upper and lower bounds of the most effective frequencies as shown in Figures 6.1 - 6.3 are similar to the upper and lower frequency limits of unstable Tollmien-Schlichting (TS) waves [11]. A preliminary analysis has shown the measured frequency limits to be of the same order of magnitude as the unstable TS-waves. However, they do not match any closer. Therefore, additional measurements are needed to confirm this.

ACKNOWLEDGEMENT

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1. Uncertainties and confidence levels, as stated in this paper, were determined by repeating measurements followed by a statistical interpretation outlined in "Experimentation and Uncertainty Analysis for Engineers" by H.W. Coleman and W.G. Steele (1989).

2. The second effect will remain even if the fluid in question were absolutely incompressible, although no acoustic waves would be observed under these conditions.

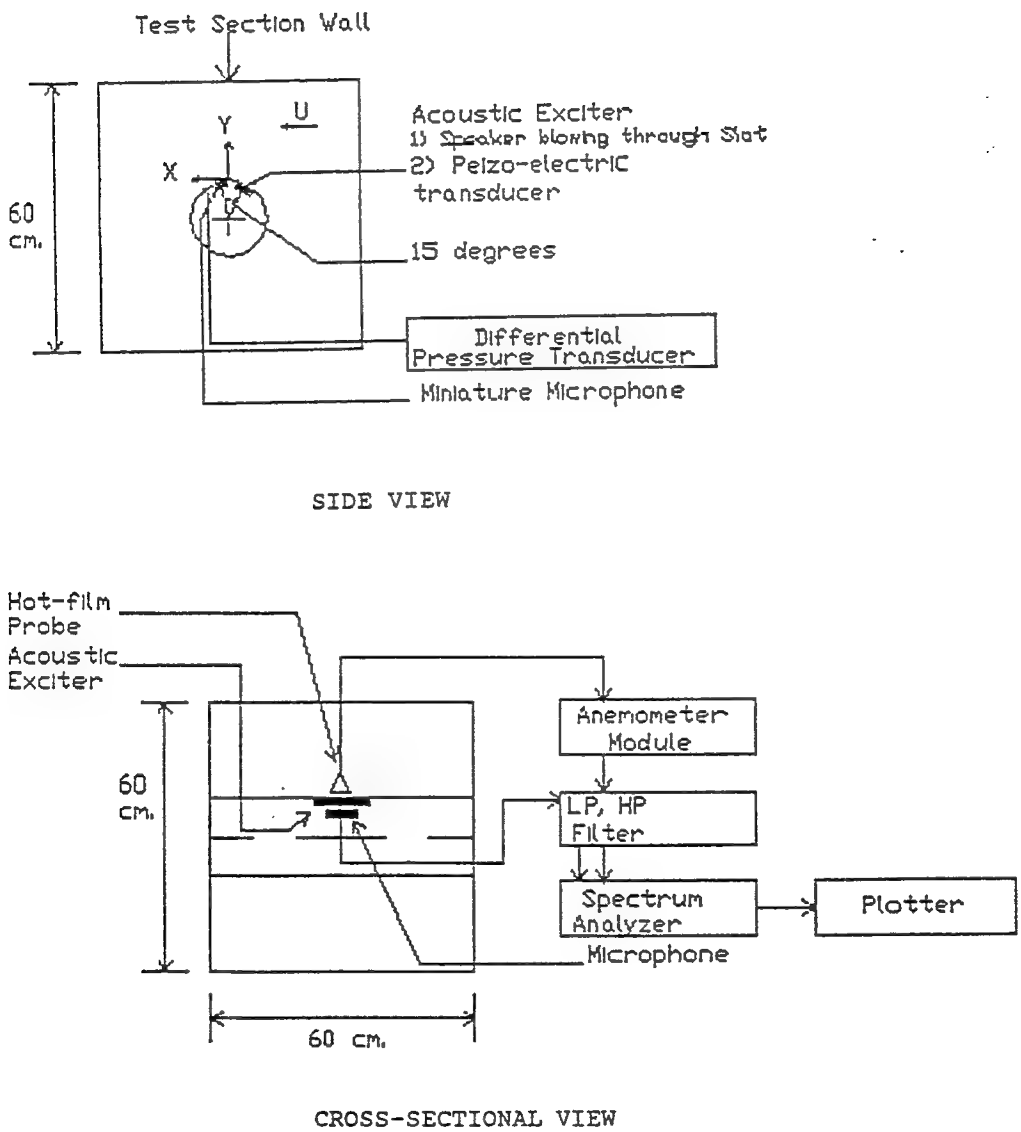

Figure 1. Schematic of the experimental setup

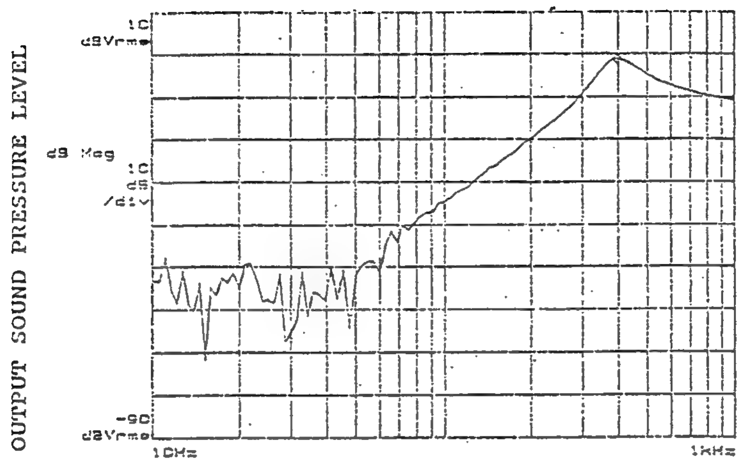

Figure 2.1. Acoustic frequency response of the speaker-slot system

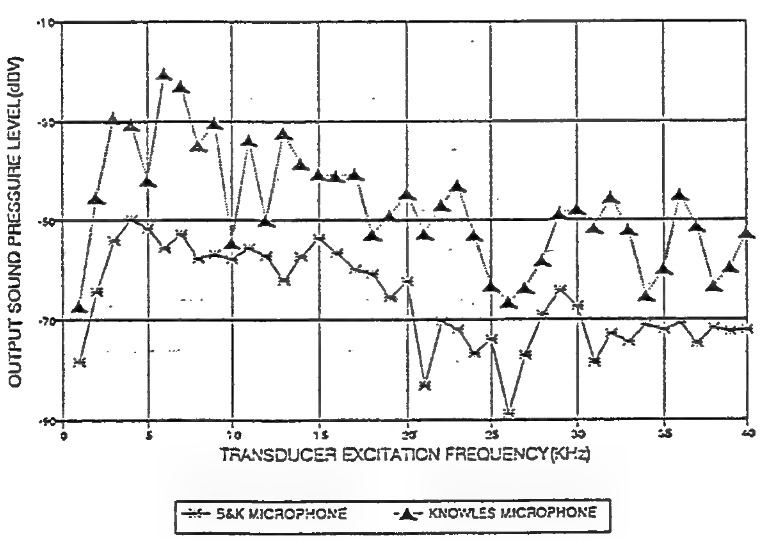

Figure 2.2. Acoustic frequency response of the piezo-electric transducer as measured by B & K Microphone and Knowles microphone under no flow conditions

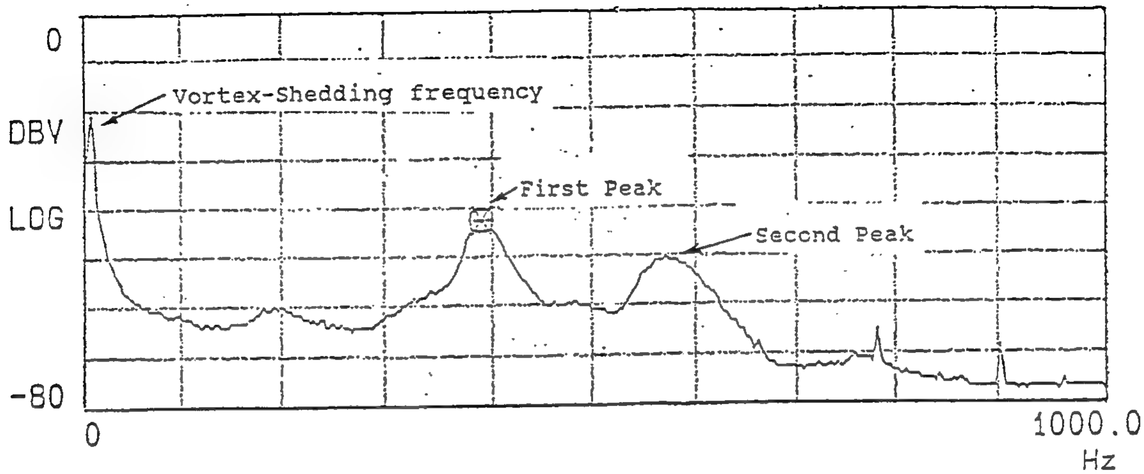

Figure 3.1. Velocity spectrum of unexcited shear layer ($Re = 6.7 \times 10^4$) Hot-Film sensor location : θ = 85 degrees from stagnation point and 2.5 mm. away from the cylinder surface.

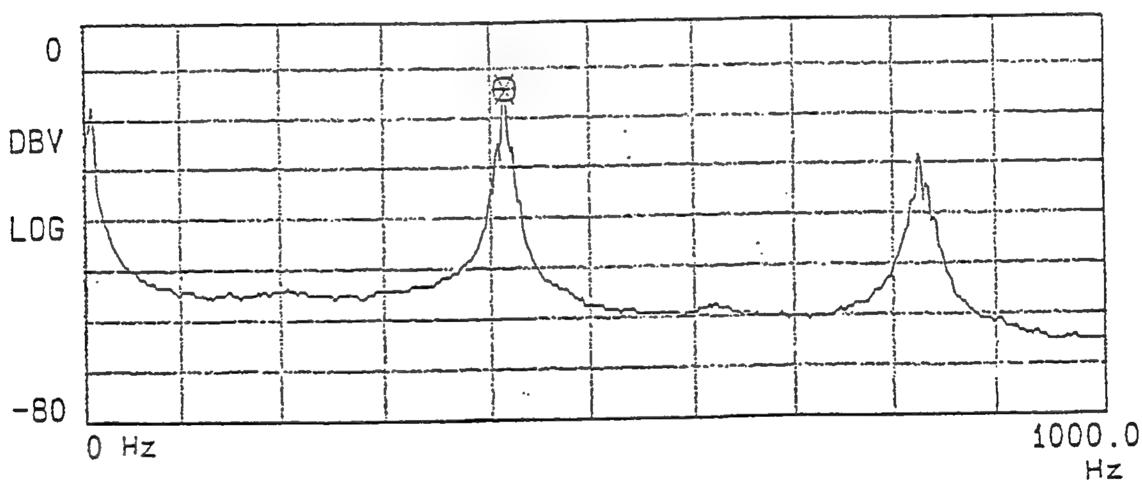

Figure 3.2. Velocity spectrum of shear layer with optimum acoustic excitation (412.5 Hz) at $Re = 6.7 \times 10^4$ Hot-Film sensor location : Same as in Figure 3.1

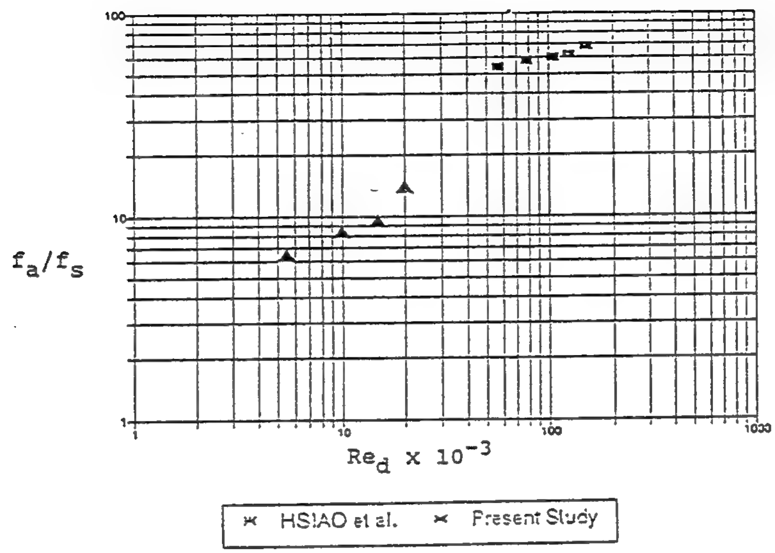

Figure 4. Variation of the optimum acoustic excitation frequency with Reynolds number

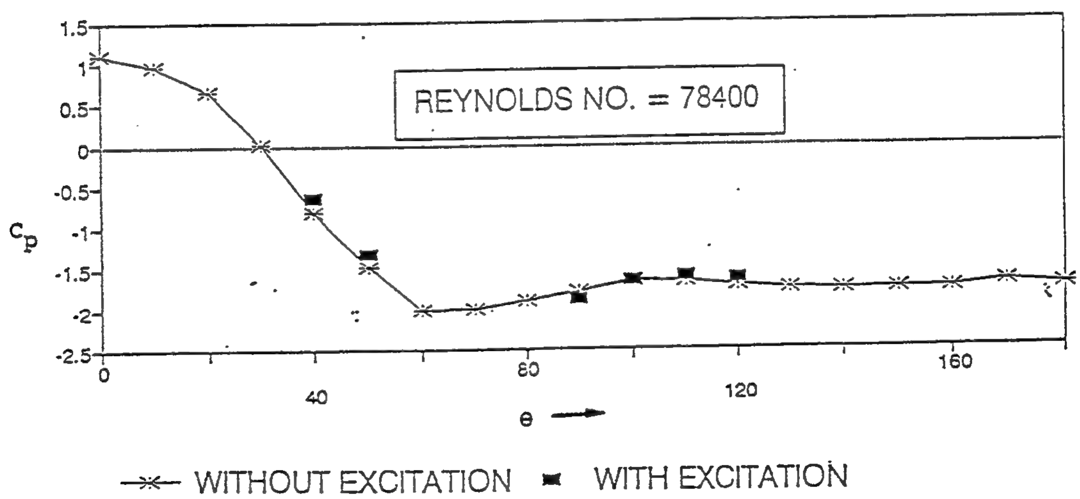

Figure 5. Effect of acoustic excitation on surface pressure distribution

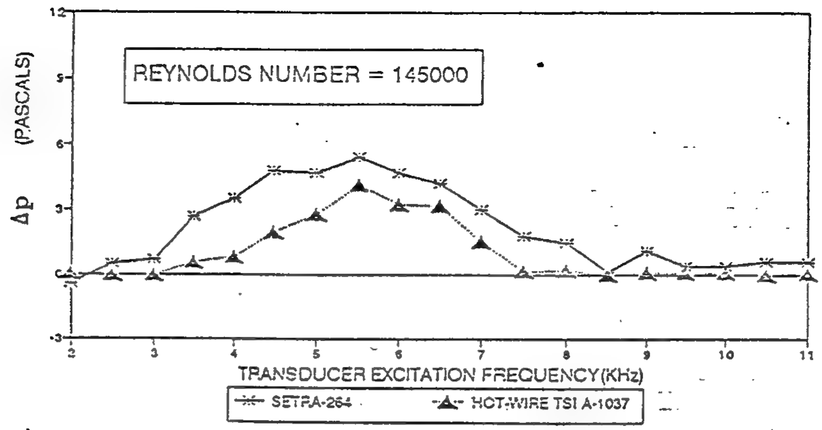

Figure 6.1. Static pressure gain at 90 degrees from stagnation point

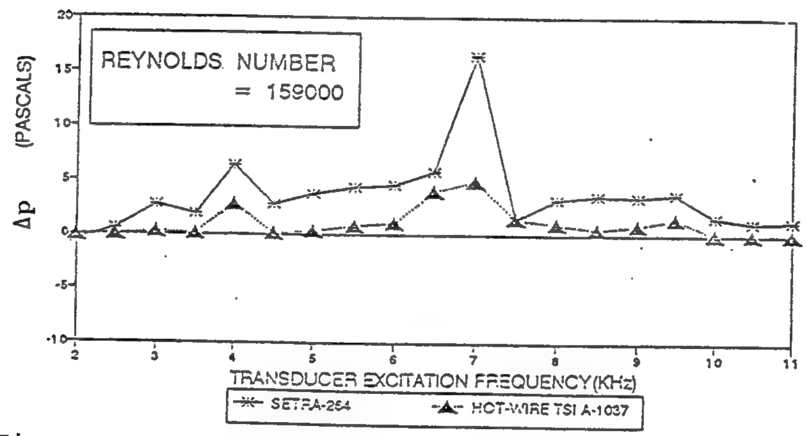

Figure 6.2. Static pressure gain at 90 degrees from stagnation point

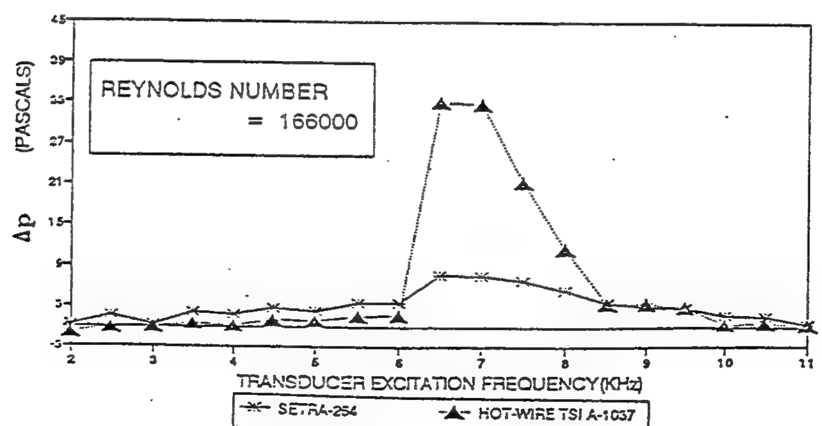

Figure 6.3. Static pressure gain at 90 degrees from stagnation point

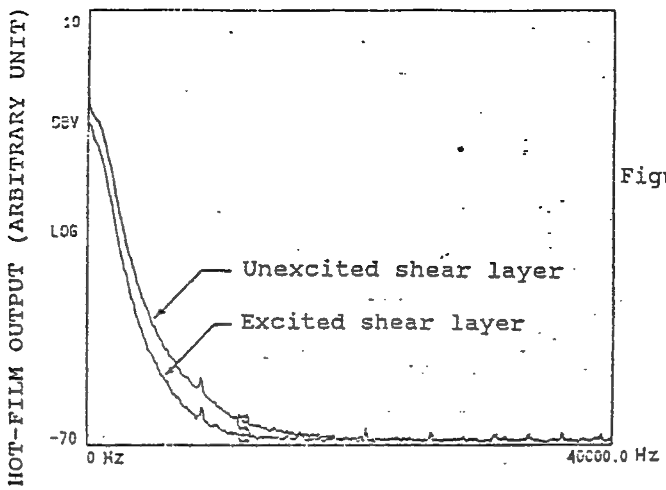

Figure 7. Hot-film output with and without excitation

$Re_d = 1.59 \times 10^5$

Excitation Frequency = 7 kHz

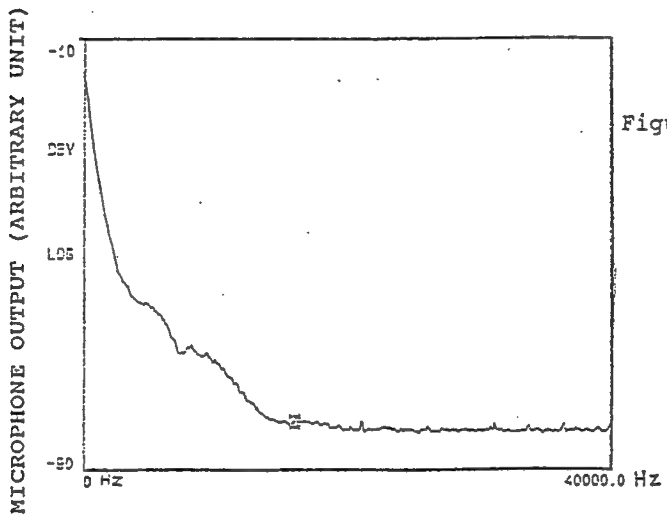

Figure 8.1. Microphone output without acoustic excitation

$Re_d = 1.66 \times 10^5$

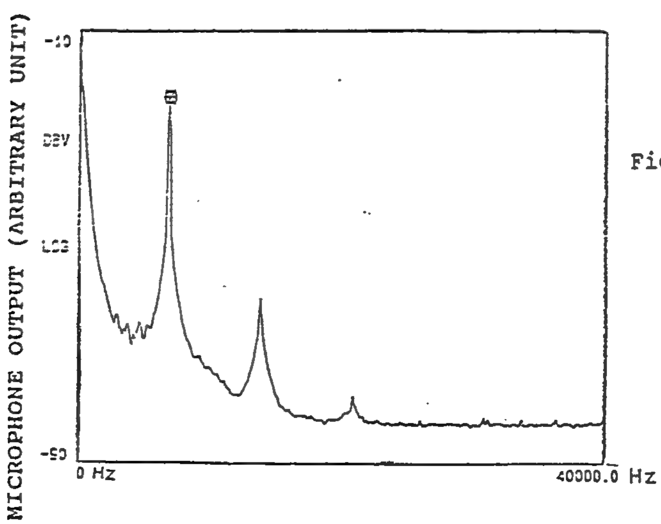

Figure 8.2. Microphone output with acoustic excitation

$Re_d = 1.66 \times 10^5$

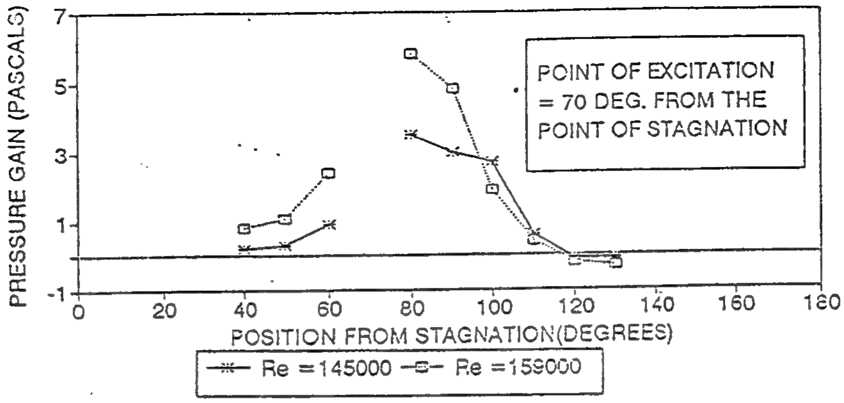

Figure 9.1. Pressure gain at various angular locations from stagnation point . f_a= 5.5 kHz for Re_d= 1.45×10^5 f_a= 7.0 kHz for Re_d= 1.59×10^5

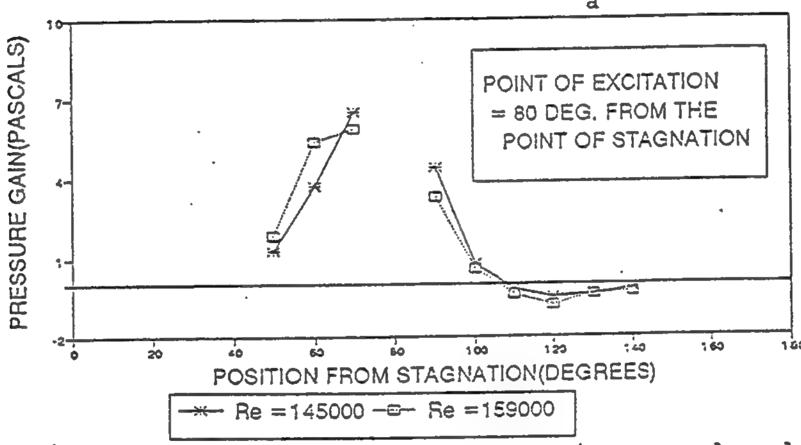

Figure 9.2. Pressure gain at various angular locations from stagnation point,
Excitation Frequencies: As mentioned in Figure 9.1.

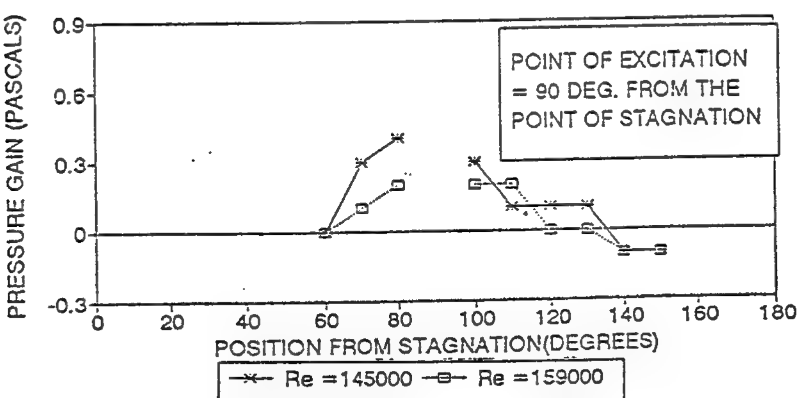

Figure 9.3. Pressure gain at various angular locations from stagnation point
Excitation Frequencies: As mentioned in Figure 9.1.

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On the Differences Between the Effect of Acoustic Perturbation and Unsteady Bleed in Controlling Flow Separation Over a Cylinder

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ABSTRACT

The effect of three different modes of acoustic excitation on an unsteady separating flow over a circular cylinder at a Reynolds number (Re_d) of about 1.5×10^5 has been investigated. The acoustic exciters included (I) a speaker mounted inside the cylinder and blowing through a narrow spanwise slot; (II) a circular piezo-electric acoustic transducer mounted flush with the surface; and (III) strip shaped flush mounted acoustic transducers. The first mode of excitation was judged most effective at about 1.3 kHz, based on changes in the time-averaged surface pressure distribution on the cylinder. The corresponding frequencies for (II) and (III) were 7 kHz and 2.25 kHz respectively. The transducers (II) and (III) did not introduce the blowing and suction effects of transducer (I). Transducer (II) increased the mean surface pressure slightly, while (I) and (III) reduced it.

1. INTRODUCTION

Flow separation is a phenomenon which is responsible for limiting the performance of rotodynamic devices like helicopter rotor blades and axial compressor blades. When the attached flow separates, a loss in lift usually follows. However, unlike flows over fixed lifting surfaces, the separation and resulting stall patterns in these cases are unsteady, and usually more complicated (e.g. dynamic stall on rotor blades and rotating stall on compressor blades). Traditional devices for flow separation control, ranging from leading edge slats and slotted flaps, to riblets and wall-mounted wing type vortex generators [1], do not operate under optimal conditions for such flows. One method to resolve this problem is to use an array of individually controllable acoustic exciters in a sensor-actuator feedback loop [2]. A similar technique using microphones as sensors and wall-suction as the actuation mechanism, has recently been used for controlling boundary layer transition on a flat plate [3]. Acoustic exciters are typically extremely simple in construction, and do not need complicated mechanisms for actuation. This makes them attractive for the applications cited above.

Experimental investigations have revealed that acoustic disturbances of suitable frequencies and amplitudes can successfully deter the process of steady and unsteady separation [3-11]. Acoustic perturbations are thought to enhance mixing by exciting instabilities inside the separated shear layer or the unseparated boundary layer. This enhanced mixing is expected to increase the momentum of the fluid close to the wall. The effect of small-amplitude acoustic excitation on the separating flow over airfoils, at low angles of attack, and low chordal Reynolds numbers, was studied by Zaman et al. [9]. The gain in aerodynamic lift was found to depend on the frequency and amplitude of the acoustic perturbation. This study [9] was

subsequently extended to estimate the acoustic frequencies and amplitudes most effective in controlling the post-stalled flows of these airfoils [10-11].

The exact manner in which an acoustic exciter interacts with a separating flow has yet to be correctly identified, since the optimum excitation frequency, expressed as a Strouhal number (St_f), has been found to vary by more than an order of magnitude for seemingly identical flow set-ups [11]. One reason for this is that acoustic pressure-density fluctuations produced by the exciter have generally been assumed to be the primary driving force, although most sound sources introduce significant velocity fluctuations as well. Most studies have used the sound pressure level (SPL) rather than the velocity fluctuation amplitudes to characterize results. For example, the effect produced by two sound sources have been assumed to be equivalent at a particular frequency if they produced the same SPL. The differences between these scalings were shown by Williams et al. [12]. Their study revealed that a separating flow responded largely to the periodic suction and blowing, and not to the radiated sound, when driven by an internally mounted acoustic speaker-type exciter.

In order to optimize the use of acoustic perturbation for separation control, an understanding of the acoustic-flow interaction mechanisms and their relationships to actuator design is crucial. With this in mind, the present authors had compared the responses of an unsteady separating flow to two different types of acoustic exciters: one which introduced significant suction and blowing (also termed as "unsteady bleed"), and one which did not [13]. The most effective excitation frequencies for the two differed by almost an order of magnitude for similar flow conditions. However, the spatial distribution of the disturbances produced by each exciter was different. Since the response of the flow was strongly dependent on the spatial location of the point of excitation, it was felt that more meaningful comparisons could be made if the transducers had similar geometries. This limitation has now been overcome by using a different transducer design, and recent experimental results from this ongoing investigation have been presented here. For the sake of completeness, comparisons have been made between all three excitation modes (Cases I and II from before, and Case III with the modified acoustic transducer).

2. EXPERIMENTAL FACILITY

Unsteady separating flow over a circular cylinder was chosen as the test flow. Acoustic exciters (described later) were mounted in the cylinder so as to perturb a portion of the flow over the surface. The cylinder (d = 168 mm in Cases I and II; d = 152 mm in Case III) was placed in crossflow in a 600-mm x 600-mm test section of a subsonic wind tunnel. The Reynolds number Re_d was varied from $0.5x10^5$ to $1.7x10^5$ for all the three cases. The freestream turbulence intensity (T_i) for this Re_d range was about 0.3%.

A single component cylindrical hot-film probe was used to measure the mean and fluctuation velocities (U_m, u_{rms} and v_{rms}) at various points: close to the acoustic exciters, in the separated shear layer and inside the unseparated boundary layer. The hot-film system had an uncertainty[1] of $\pm$6 cm/s (95% confidence level) for velocity magnitudes in the range of 5 to 30 m/s. Additionally, a pressure transducer (SETRA Model 264), communicating sequentially with several static-pressure taps, was used to detect changes in mean (i.e. time averaged) static pressures on the cylinder surface resulting from the acoustic excitation. The time-averaged pressures had an uncertainty of $\pm$1.432 Pa in 75 Pa within a 95% confidence level.

Three different modes of acoustic excitation (Cases I, II and III) were studied :

In the first case, a 50-mm diameter speaker was mounted under the solid boundary of the 168 mm diameter cylinder. The speaker, when driven by a sinusoidal signal generator through a power amplifier, was capable of perturbing the wall flow with acoustic radiation and periodic suction/blowing of air through a 2-mm wide and 25-mm long spanwise rectangular slot on the surface of the cylinder (see Figure 1). The angular location of the slot was maintained close to the unperturbed mean separation point of the flow so that maximum flow-acoustic interaction could be achieved. For similar experimental conditions (i.e. similar Reynolds numbers, aspect ratios, freestream turbulence

intensity etc.), Achenbach [14] estimated the angular position of the separation point at 78-90 degrees from the forward geometric stagnation point. The corresponding minimum surface-pressure points were found to lie between 70-80 degrees from the stagnation point. The acoustic frequency response of the speaker-slot system, when driven with a 10-volt peak-to-peak sinusoidal signal, is shown in Figure 2.1. The sound pressure level (SPL) at the slot exit was kept constant at 115 db for all frequencies of excitation considered.

In Case II, the speaker-slot system was replaced with a 25-mm diameter piezo-electric transducer, mounted flush with the cylinder surface and exposed to the flow. The transducer radiated sound when driven with the signal generator and amplifier. The SPL was kept constant at 90 dB. The frequency response of the mounted piezo-electric transducer was recorded using a 1/4 inch (6-mm) B & K condenser microphone (Cartridge type 4147). The most prominent resonant frequency of the transducer, was observed to be close to 6 kHz (Figure 2.2). In addition to the pressure transducer, and the hot-film probe, a miniature microphone (KNOWLES Model BW-1789) was also flush-mounted on the cylinder surface, immediately downstream of the piezo-electric acoustic transducer. Figure 2.2 shows that the responses of both microphones (Knowles and B & K) are similar, when excited with the mounted piezo transducer in the 1 to 40 kHz range; the Knowles microphone being more sensitive. Experimental details of the above-mentioned modes of excitation can be found in reference [13].

Since the transducer in Case II behaves as a distributed surface source of sound, it was felt that a better comparison with Case I could be obtained if a line source was used instead. This was done in Case III, where an array of flush mounted strip-shaped transducers (1.6-mm wide and 570-mm long, with 1.6 mm space between strips) oriented parallel to axis of the cylinder was used. These were developed for the purpose of investigating the effect of localized (in the streamwise direction) excitation. Therefore each strip could be individually energized. Additionally, each strip could be used as a sensor for wall pressure fluctuations. Proprietary considerations currently preclude revealing additional construction details of this transducer. The surface displacement of this transducer, was measured to be very small (order of 10^{-3} mm). Therefore, the direct momentum transfer due to wall motion, such as effects similar to blowing and suction could be ignored. Wall compliancy effects were also negligible. In this sense this transducer is similar to the piezo-electric transducer of Case II. The frequency responses of three representative strips as measured with the B & K microphone are shown in Figure 2.3. The variation in response along the length of each strip was within 7%.

3. RESULTS AND DISCUSSION

Experiments with all the types of exciters showed evidence of interaction with the flow. There were however significant differences. These are described below.

Case 1: (Speaker blowing through slot)

Figure 3.1 shows a typical averaged frequency spectrum of the velocity, at $Re_d = 0.67 \times 10^5$. This was measured with the hot-film sensor slightly downstream of the separation point in absence of any acoustic excitation. The first peak at 9.8 Hz corresponds to f_s, the vortex-shedding frequency of the cylinder. The next peak (which is marked in the figure) is thought to correspond to the instability frequency of the separated shear layer, since this and other higher frequency peaks do not correspond to the harmonics of the shedding frequency f_s or any of the wind-tunnel resonant frequencies (e.g. longitudinal, transverse etc.).

The largest change in mean static pressures was observed for f_a = 412.5 Hz at an Re_d of 0.67×10^5. This is close to, but slightly different from the instability frequency of the separated shear layer. This suggests a lock-in phenomenon at 412.5 Hz. Figure 3.2 shows the averaged velocity spectrum when the flow is excited at the corresponding lock-in frequency. A similar lock-in phenomenon occurred at higher Reynolds numbers also. However, as the Re_d was increased to 1.48×10^5, the peaks in the unexcited velocity spectrum got buried in the ambient noise (Hence, these figures have not been shown). The optimum frequency of excitation for lock-in was found to

increase to 1.3 kHz. The noise in the unexcited velocity spectrum increased presumably due to larger velocity fluctuations induced by higher free-stream velocities. An additional factor was the disturbances caused by the slot. Therefore, a frequency sweep procedure was used to estimate the lock-in frequencies at higher Re_d values.

The measurement of time-averaged static pressures on the surface of the cylinder showed that the minimum pressure point on the cylinder moves downstream as Re_d is increased. Figure 4 shows that a small change occurs in the mean static pressure distribution when the speaker is energized. The decrease in static pressure due to acoustic excitation is expected to be maximum immediately downstream of the point of excitation [7,15]. However, no pressure port could be provided in the vicinity of the slot due to the relatively large size of the speaker.

The role of direct momentum transfer in the flow-perturbation interaction was studied next. This was caused by the periodic suction and blowing of air (or unsteady bleed) through the slot. The root mean squared (rms) velocity fluctuations at the slot exit was measured with the hot-film sensor when the speaker was driven at the optimum lock-in frequencies under no flow conditions. The lowest measured fluctuations (v'_{rms}) were about 0.5 m/s. These were much larger compared to the largest acoustic particle velocities, which were about 3 mm/s. The acoustic particle velocities were estimated from the acoustic impedance (ρ.c) and pressure fluctuations at the slot exit. Hence two perturbation mechanisms coexist; the acoustic pressure fluctuations, and the velocity fluctuations due to alternate blowing and suction through the slot[2]. As frequencies are increased, the contribution due to unsteady bleed reduces. Most previous investigations do not explicitly acknowledge the unsteady bleed effect.

The acoustic wavelengths λ (i.e. c/f_a), for the optimal values of f_a at which the flow appeared to be receptive to the perturbation, were at least two orders of magnitude higher than the boundary layer thickness near separation. A study of flow separation control by unsteady bleed techniques (or alternate blowing and suction) by Williams et al. [12] also suggests similar phenomena.

Case 2: (Excitation with the circular Piezo-electric transducer)

The flow-acoustic interaction in this case suggests a negative effect on drag reduction due to acoustic perturbation alone. The "pure" acoustic excitation reduced the mean and fluctuating components of fluid velocity inside the separating shear layer, as measured by the hot film anemometer. Figure 5 shows the gain in static pressures as a function of excitation frequency for flow Re_d of 1.59×10^5. The pressure transducer measured static pressures at the downstream end of the 25-mm diameter piezo-transducer, whose center was located 80° from stagnation. The decrease in time-averaged local velocity heads ($\rho U_m^2/2$), as measured close to the pressure port locations by the hot-film anemometer, is assumed to reflect a corresponding increase in local static pressures.

The most effective range of excitation frequencies was in the order of several kHz. The corresponding wavelengths in air were still about an order of magnitude larger compared to the boundary layer thickness. The maximum measured wall pressure gain occurred at a Reynolds number of 1.59×10^5, when excited at 7 kHz. Figure 6 shows the velocity spectra of the unexcited and excited shear layers at this Reynolds number. The magnitudes of velocity-fluctuations in the shear layer, centered around the respective excitation frequencies, decreased as a result of pure acoustic excitation. Figures 7 shows the pressure fluctuation spectra measured by the Knowles microphone. These show that the pressure fluctuations are enhanced at the excitation frequency and its harmonics. Figure 8 shows changes in mean static-pressures on the surface of the cylinder for the 7 kHz excitation. The pressure gains were observed to be maximum when the location of the acoustic source was near the point of mean separation (80°).

Although the piezo-electric transducer effectively eliminated the effect of direct blowing and suction, its relatively large size limited the scope of estimating the optimal spatial location of the point of excitation, since the movement of the separation-point over a vortex-shedding cycle was less than the diameter (25-mm) of the piezo-electric transducer. Additionally, the surface of the piezo

transducer undergoes complex vibrational modes when excited at 7 kHz (based on laser-Doppler vibrometer measurements, [16]), thereby introducing significant three-dimensional perturbations into the boundary layer. It is difficult to ascertain the effects of these complex excitation modes on the flow.

CASE 3: (Excitation with strip-shaped acoustic transducers)

The transducer strips in this case generated two-dimensional perturbations similar to Case I. The strips were excited one at a time, and changes in mean static pressures on the cylinder surface were noted. Once the optimum angular location of the point of excitation was determined, the effect of driving multiple strips (in phase) centered around this point was determined. For $Re_d=1.54\times10^5$, largest changes in mean static pressures on the cylinder surface were observed when two adjacent strips, spanning the region between 72° and 74° from stagnation, were excited at 2.25 kHz. Figures 9.1 and 9.2 show the spectra of velocity and wall-pressure fluctuations immediately downstream of the excitation point at this Re_d, in absence of any excitation. The pressure spectrum (sensed by a transducer strip at 78°) shows a peak at 2.25 kHz. Signals from transducer strips at other locations also showed responses at this frequency but did not display this peak. It is interesting to note that the transducing strips did not have any resonances around this frequency (Figure 2.3). This leads us to believe that the 2.25 kHz corresponds to a flow-induced instability near the separation point.

Figure 10 shows the changes in mean surface pressures as a result of exciting the two strips between 72° and 74°. The pressure distribution over the cylinder in absence of acoustic excitation (Figure 10) shows that the strip transducers do disturb the flow slightly. This was primarily due to the presence of small surface irregularities resulting from mounting the transducers on to the test cylinder. The magnitudes of the pressure changes due to acoustic excitation are significantly higher than those induced by surface irregularities. The changes are larger than those in Cases I and II. Hot-film measurements were made close to the cylinder surface, upstream and downstream of the optimum excitation region. These showed increases in the mean velocity (U_m), accompanied by a reduction in the velocity fluctuations (u_{rms} and v_{rms}) when the strips were energized.

In the earlier paper by the present authors [13], the possibility of triggering unstable Tollmien-Schlichting (TS) waves was discussed, since the Re_d values used were close to the critical values for the cylinder. In a recent numerical study Frendi et al. [17] investigated the interaction of planar acoustic waves emanating from a section of a flat plate with a supersonic boundary layer over it. Their investigations have revealed that pressure fluctuations in the boundary layer are affected most by sound at frequencies which are submultiples of the lowest unstable TS frequency, and correspond to one of the natural frequencies of the plate. Additionally, the magnitude of the interaction is higher at frequencies which correspond to the lower vibrational modes. The acoustic waves were also found to introduce inflections in the boundary layer velocity profile and enhance the movement of vorticity from the wall into the flow. Although the present flow is subsonic, the mechanisms for promoting TS-instabilities are probably similar for Case III. The peak in the pressure fluctuation spectrum (Figure 9.2) probably corresponds to a submultiple of the TS-frequency. Finally, Frendi et al. have also reported a change in local mass flux fluctuations over the sound source even when TS waves are absent.

4. CONCLUSIONS AND RECOMMENDATIONS

Considerable differences have been found in the way different acoustic sources interact with unsteady separating boundary layers. The nature of perturbation effected by a speaker seems to be predominantly mechanical (i.e. blowing and suction) rather than acoustic. This is evident from differences in frequency range in which each device performs best. Additional arguments based on comparisons of SPL and velocity fluctuations at the slot of a speaker-slot system [12,13] seem to support this view.

The speaker-slot exciter (Case I) increased velocity fluctuations near the wall, while a

reduction occurred in the other two cases. Additionally, in Case II, the mean static pressure on the surface of the cylinder increased near the point of excitation, while a decrease is noted in Cases I and III. Results of Hsiao et al. [7] for flow over a cylinder also show a decrease in pressure. The present results with slot blowing (Case I) do not include any pressure measurements in the vicinity of the slot. Hence, the trend (Figure 2.3) is unclear. It should be noted however, that the results of Hsiao et al. [7], are for low fully-laminar Re_d values, while the present results are in the transitional to turbulent regime.

The principal difference between the transducers in Cases II and III is their geometry and resulting vibrational modes. The circular transducer in Case II increased the mean pressure above it, while the other strip-type transducers in Cases I and III reduced the pressure. Additionally, in Case III, differences were noticed when single versus multiple strips were excited. These may be explained in terms of three-dimensional effects, since the separation pattern on a circular cylinder for the Re_d values considered is three dimensional [18]. Since large-scale velocity and pressure fluctuations due to vortex-shedding are superposed on small-scale instabilities, the phase relation of the two is of great significance [6,19]. Although the transducer in Case III is capable of doing this, the present studies were limited to exciting the strips in-phase since the correct phase relationships for optimal excitation have not yet been determined. The pressures sensed by the individual strips contain a wide range of frequencies, and some form of filtering needs to be implemented in order to track the separation point more accurately.

NOMENCLATURE

c = Velocity of sound in fluid
C_L = Lift coefficient = $2L/(\rho U_\infty^2)$
C_p = Pressure coefficient = $(p-p_\infty)/0.5\rho U_\infty^2$
d = Diameter of the cylinder
= 168 mm (in Cases I and II)
= 152 mm (in Case III)
f_a = Acoustic excitation frequency
f_s = Vortex shedding frequency
h = Height of wind-tunnel test section = 60 cm
L = Lift force
l = Length of the cylinder = 60 cm
p = Surface static pressure
p_∞ = Upstream static pressure
q = Aspect Ratio = l/d
Re_d = Reynolds Number based on cylinder diameter
= $U_\infty d/\nu$
S = Blockage ratio = d/h
SPL = Sound pressure level (dB)
St_f = Strouhal Number based on excitation frequency
T_i = Freestream turbulence intensity
= $(u'^2)^{0.5}/U_\infty$ = .30 %
U_∞ = Upstream velocity
U_m = Streamwise mean velocity
u' = Streamwise velocity fluctuation
v' = Normal velocity fluctuation
x = Streamwise distance measured from geometric forward stagnation point
y = radial distance measured from cylinder surface
ρ = Fluid density
ν = Fluid kinematic viscosity
Θ = Angular position from geometric forward stagnation point
λ = Wavelength of sound

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[1] Uncertainties and confidence levels, as stated in this paper, were determined by repeating measurements followed by a statistical interpretation outlined in reference [20].

[2] The second effect will remain even if the fluid in question were absolutely incompressible, although no acoustic waves will be observed under these conditions.

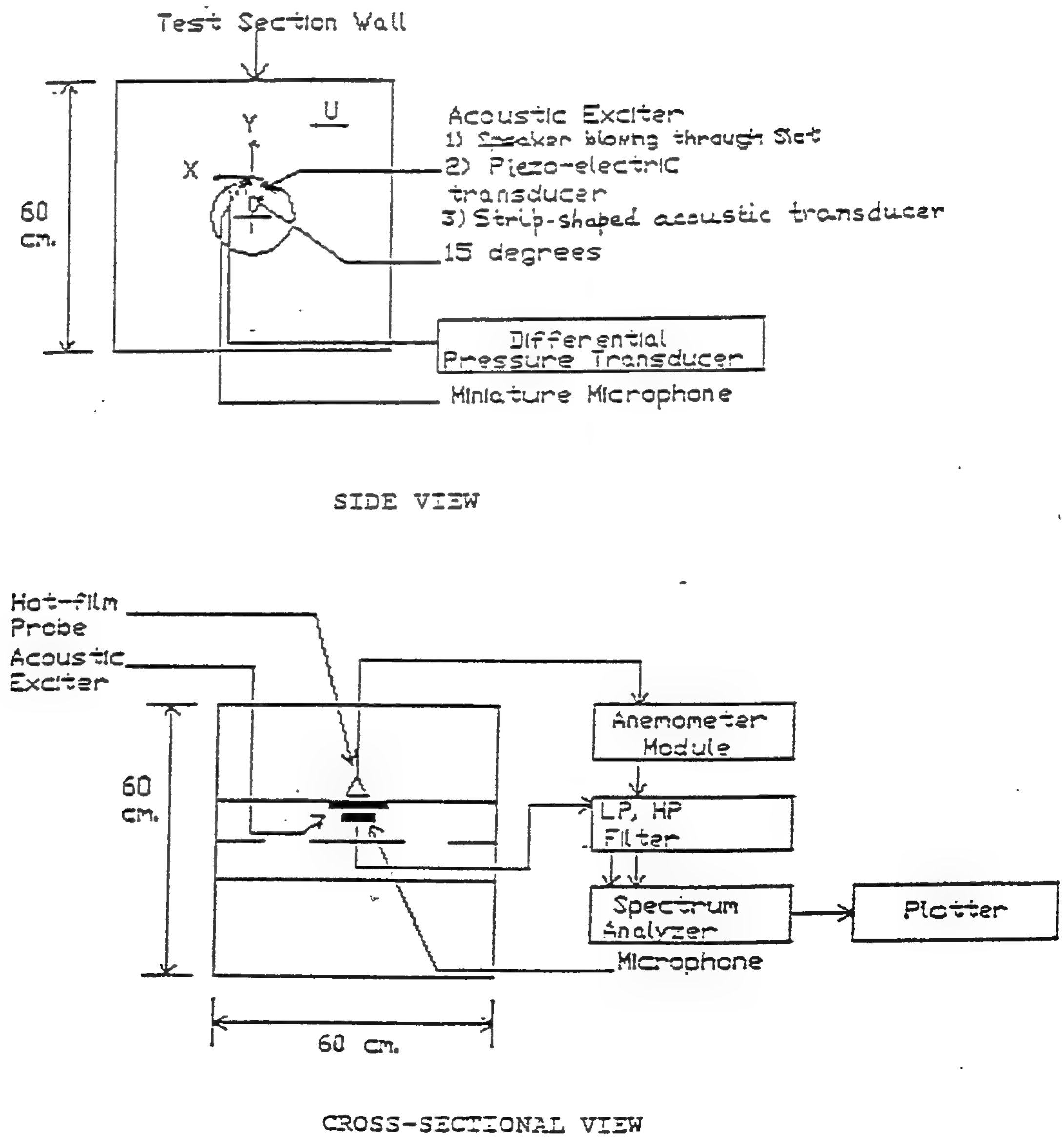

Figure 1. Schematic of the experimental setup.

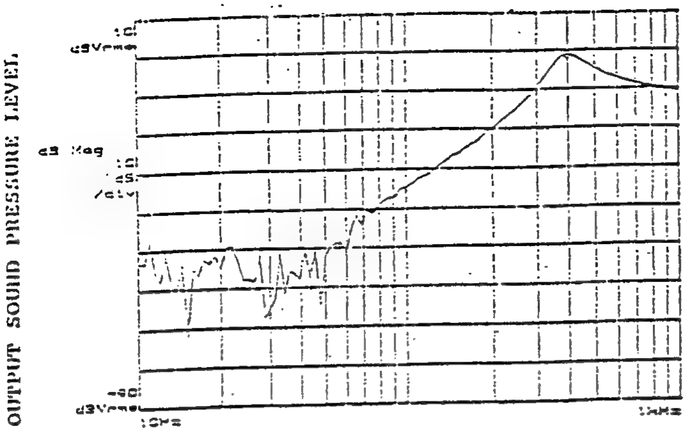

Figure 2.1. Acoustic frequency response of the speaker-slot system.

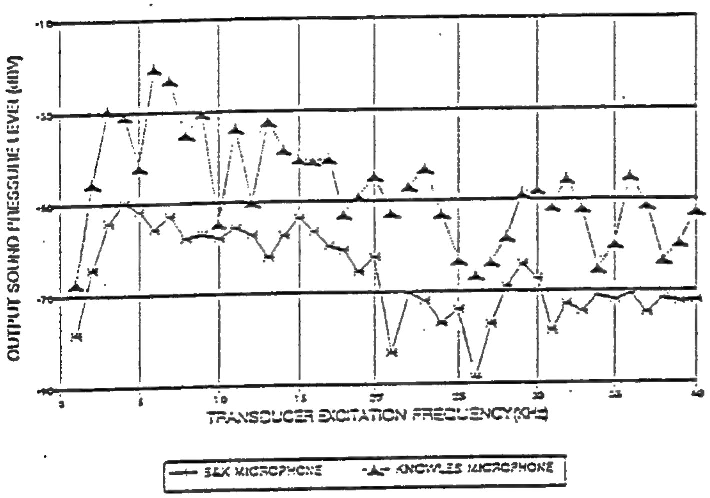

Figure 2.2.

Acoustic frequency response of the piezo-electric transducer as measured by B & K microphone and KNOWLES microphone under no flow conditions.

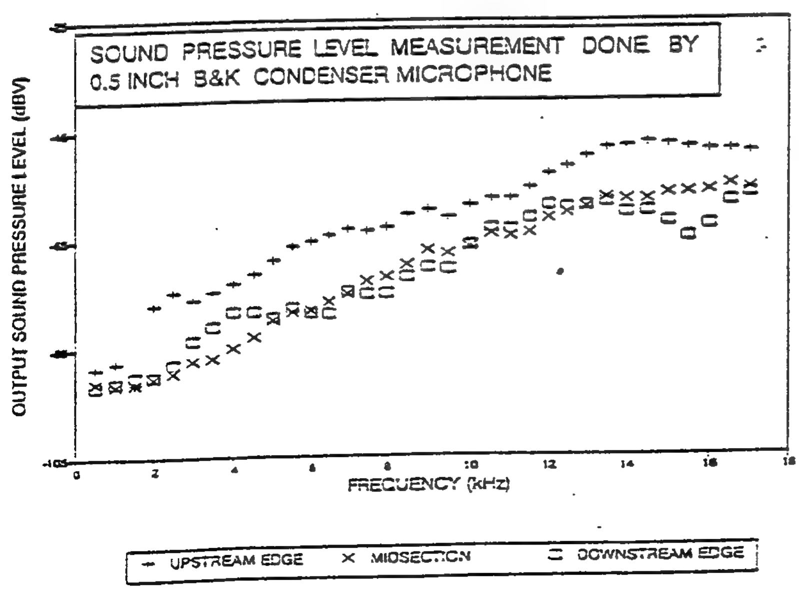

Figure 2.3.

Acoustic frequency response of strip-shaped acoustic transducer as measured by B & K microphone at three different locations under no flow conditions.

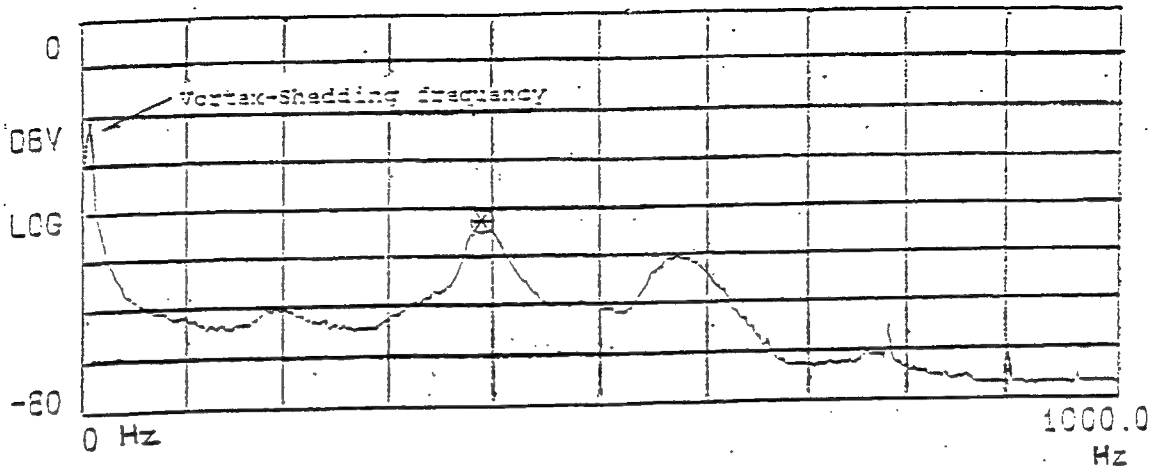

Figure 3.1. The velocity spectrum of unexcited shear layer (Re = 6.7×10^4). Hot-film sensor location : Θ = 85 degrees from stagnation point and 2.5 mm away from the cylinder surface.

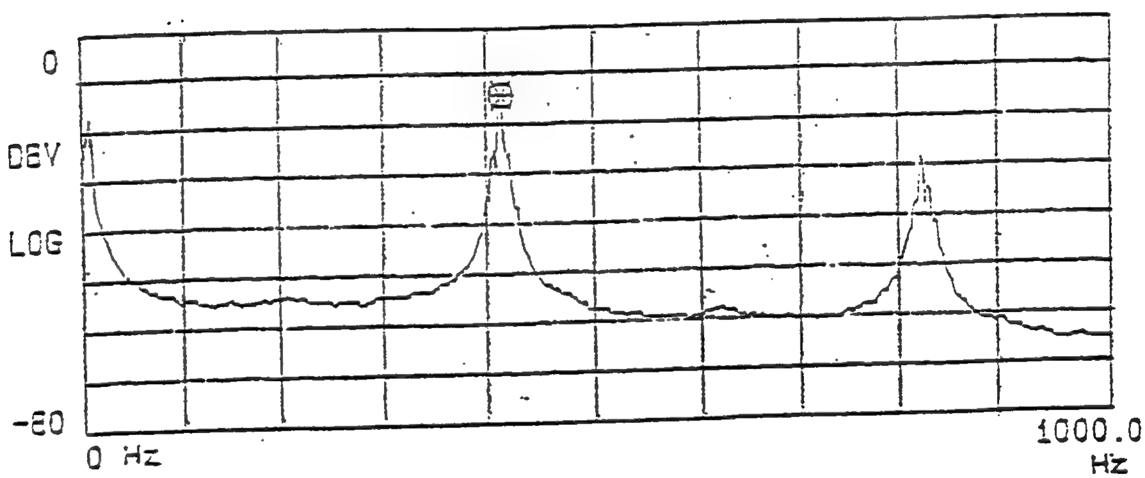

Figure 3.2 The velocity spectrum of shear layer with optimum acoustic excitation (412.5 Hz) at Re = 6.7×10^4. Hot film sensor location : same as in Figure 3.1.

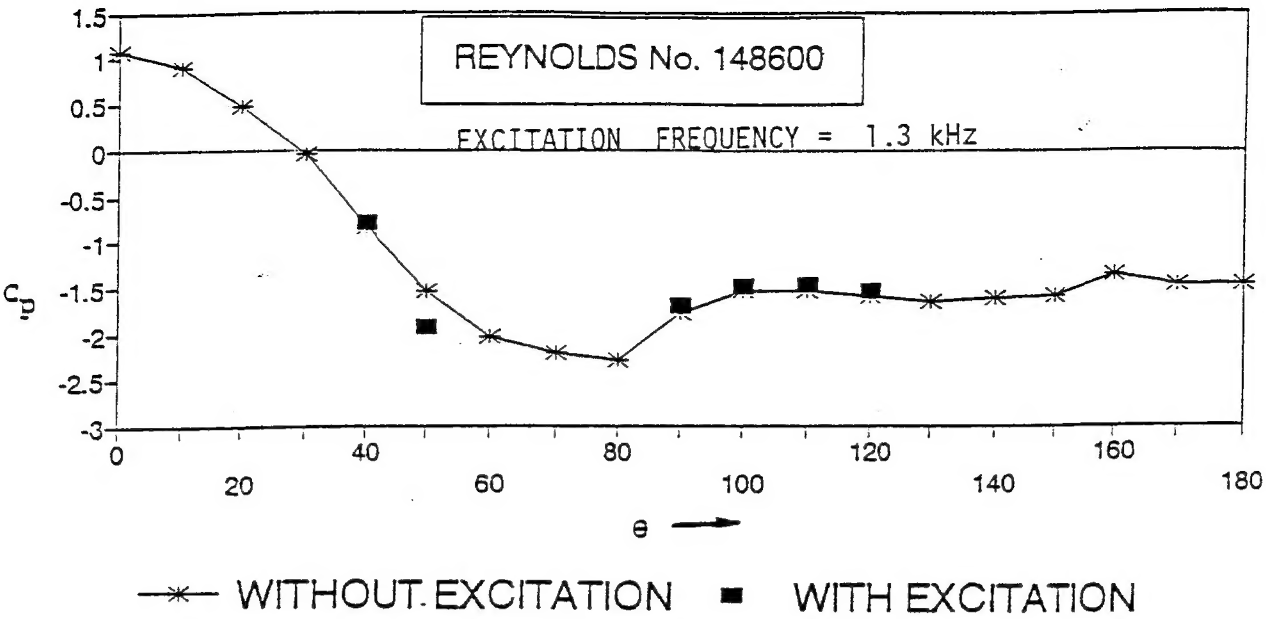

Figure 4. The effect of acoustic excitation on surface pressure distribution.

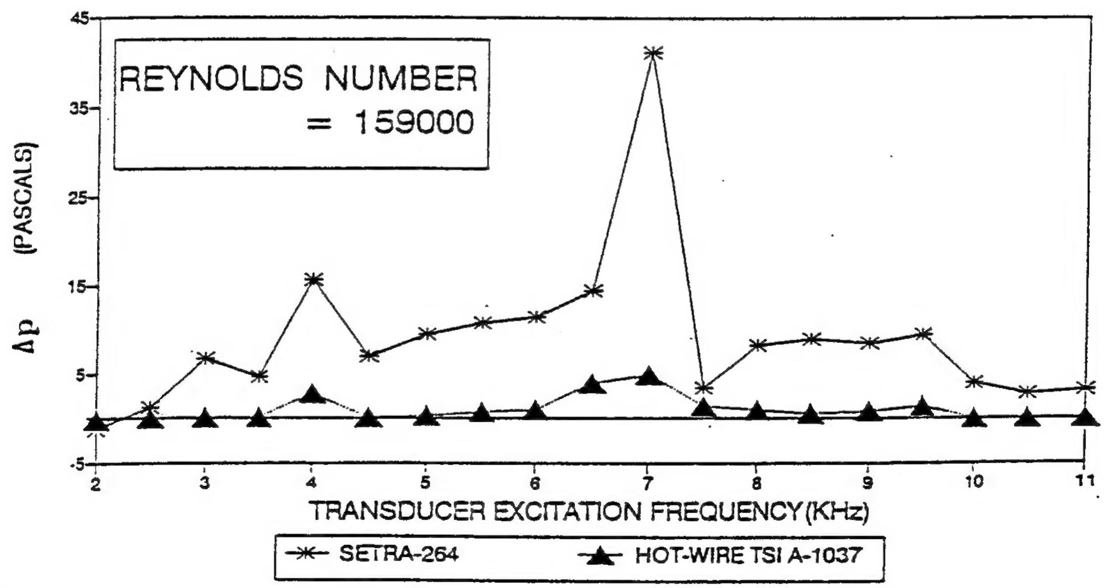

Figure 5. Static pressure gain at 90 degrees from stagnation point.

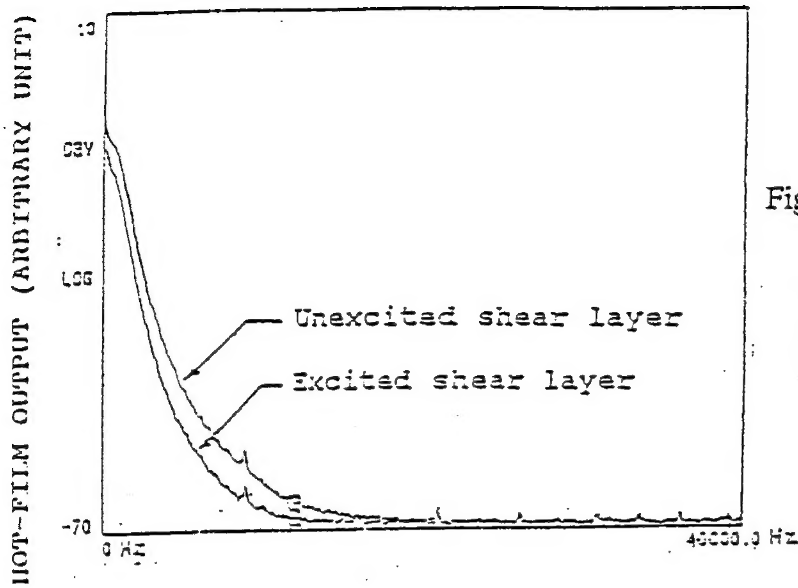

Figure 6.

Hot-film output with and without excitation.
$Re_d = 1.59 \times 10^5$
Excitation frequency = 7 kHz

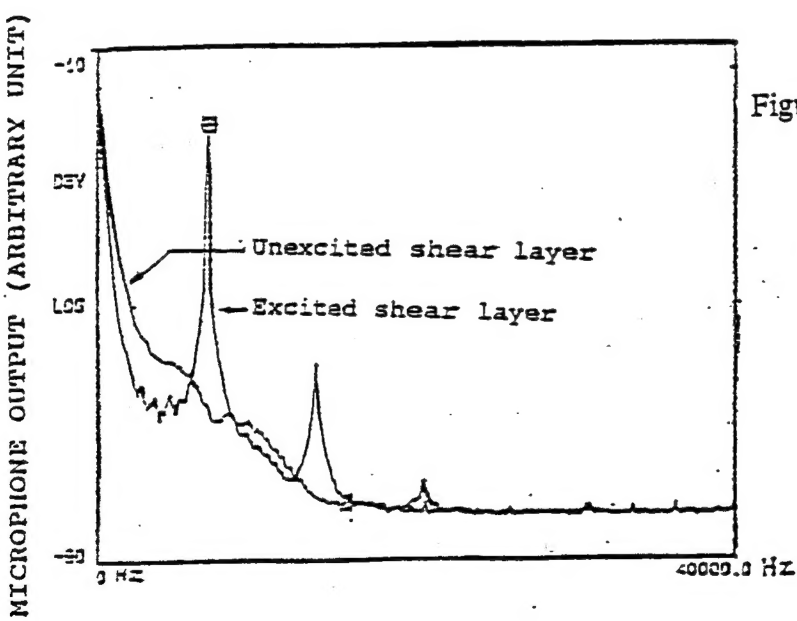

Figure 7.

Microphone output with and without acoustic excitation.
$Re_d = 1.66 \times 10^5$.

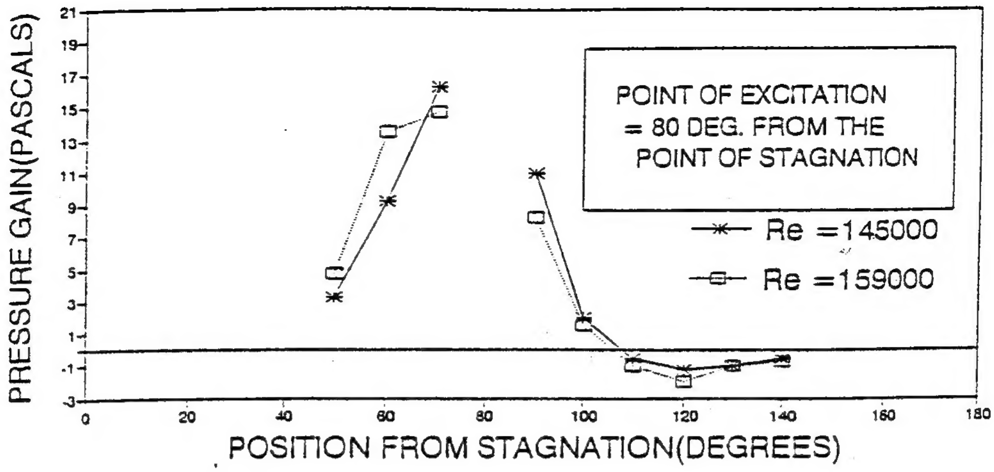

Figure 8. Pressure gain at various angular locations from stagnation point.
Excitation frequencies: $f_s = 5.5$ kHz for $Re_d = 1.45 \times 10^5$
$f_s = 7.0$ kHz for $Re_d = 1.59 \times 10^5$

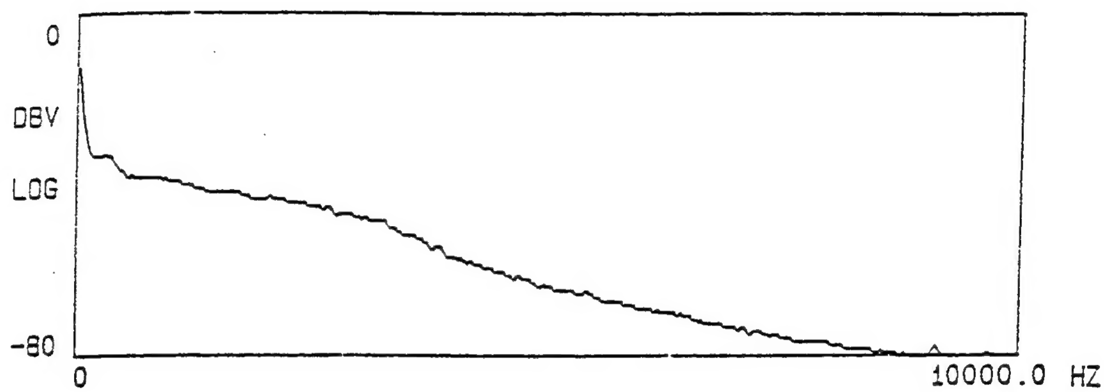

Figure 9.1. The velocity spectrum of unexcited shear layer ($Re_d = 1.5 \times 10^5$)
Hot-film sensor location : Θ = 82 degrees from stagnation point.

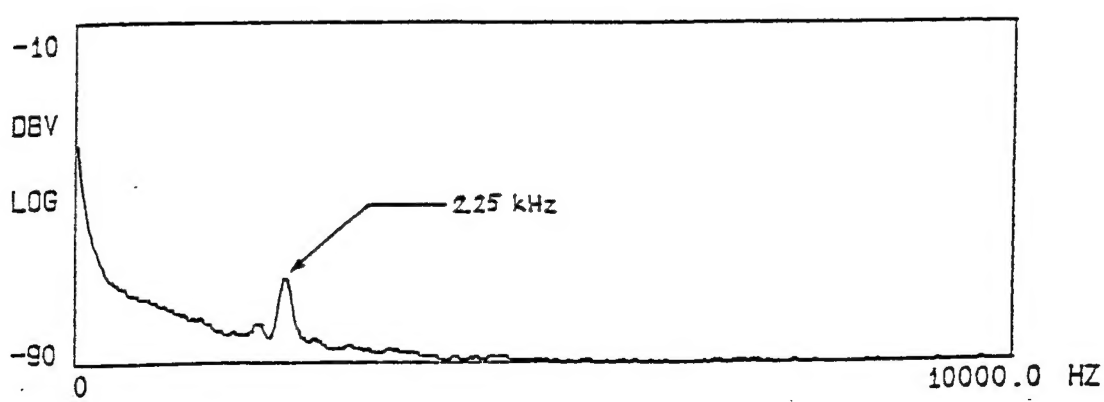

Figure 9.2 The pressure fluctuation spectrum of unexcited boundary layer ($Re_d = 1.5 \times 10^5$) at 78 degrees from stagnation.

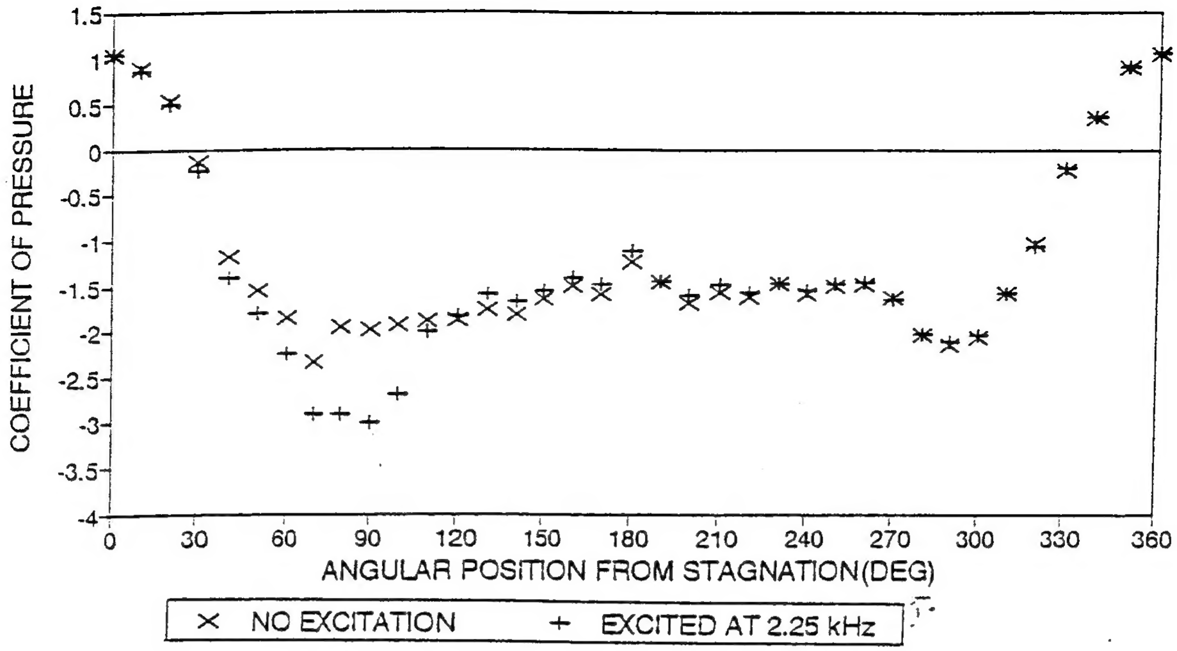

Figure 10. Effect of acoustic excitation on surface static pressure distribution. $Re_d = 1.5 \times 10^5$. Acoustic excitation at 72-74 degrees from stagnation.